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# METHODOLOGY FOR THE SYSTEMS ENGINEERING PROCESS
## Volume I: System Functional Activities

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16. ABSTRACT

This study examines systems engineering in terms of functional activities that are performed in the conduct of a system definition/design, and describes system development in a parametric analysis that combines functions, performance, and design variables.

The description of the functional activities that constitute systems engineering was addressed from the point of view that as a meaningful technology in the development of complex systems, systems engineering must be described as a discipline. Emphasis was placed on identification of activities performed by design organizations, design specialty groups, as well as a central systems engineering organizational element. Identification of specific roles and responsibilities for "doing" functions, and monitoring and controlling activities within the system development operation were emphasized.

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## FOREWORD

This report is submitted in accordance with the requirements of Contract NAS8-27567. Martin Marietta Corporation submits this report in three volumes as follows:

Volume I--System Functional Activities (NASA CR-61380)

Volume II--Technical Parameters (NASA CR-61381)

Volume III--Operational Availability (NASA CR-61382)

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## INTRODUCTION

Systems engineering is a recognized factor in aerospace system development both as a practical approach and an objective for development of large and complex systems. The technology that makes up systems engineering has been difficult to describe because it addresses many aspects of engineering operations and the process of development itself. This study addresses the subject in terms of functional activities that are performed by engineering organizational elements involved in development operations, and examines the systems engineering problem from the point of view of technical parameter relationships in development of a large system; no attempt has been made to cover in scope or depth all aspects of this technology.

## SUMMARY

A. This study examines systems engineering in terms of functional activities that are performed in the conduct of a system definition/design, and describes system development in a parametric analysis that combines functions, performance, and design variables.

The description of the functional activities that constitute systems engineering was addressed from the point of view that as a meaningful technology in the development of complex systems, systems engineering must be described as a discipline. Emphasis was placed on identification of activities performed by design organizations, design specialty groups, as well as a central systems engineering organizational element. Identification of specific roles and responsibilities for "doing" functions, and monitoring and controlling activities within the system development operation were emphasized.

The description of systems engineering functional activities and their interactions was directed to:

1) systems engineering functions versus system elements;

2) systems engineering functions versus phases of development;

3) the composite of items 1 and 2.

These treatments were found necessary because interaction of three correlated variables can only be described coherently by superposition.

The complexity of systems engineering is compounded by organizational as well as hardware and software complexity. In this study it was found that the description of the activities applied equally well for the case of one or many organizations; that the hierachy functional elements of systems engineering was the same at any level. In the application of systems engineering for a system project organization, each contractor and agency involved in the development is the same, and the interrelationships of these systems engineering disciplines make up an integrated set of activities aimed at achieving a complete and integrated system that best meets the mission requirements at minimum cost.

B. Development of parametric relationships among technical parameters is an approach to describing a complex system in a logic network display that gives visibility to the primary parameters of concern in controlling development of a complex system.

In this study a scheme was developed based on starting the logic networks from the primary development and mission factors that are of primary concern in an aerospace system. This approach required identification of the primary states (design, design verification, premission activity, mission, postmission), identification of the attributes within each state (performance capability, survival, evaluation, operation, etc), and then developing the generic relationships of variables for each branch. To illustrate this concept, an example system was used that involved a launch vehicle and payload for an Earth orbit mission. Examination showed that this example was sufficient to illustrate the concept; a more complicated mission would follow the same approach with more extensive sets of generic trees and more correlation points between branches.

This study showed that in each system state (production, test, and use), a logic could be developed to order and classify the parameters involved in translation from general requirements to specific requirements for system elements.

The technique of graphical description of technical parameter relationships was found to have limitations as a result of the huge degree of correlation that exists among parameters of a complex system. Technical parameter trees developed for the reference system show examples of these limitations. A more sophisticated method of determining and showing parameter relationships is needed.

C. The third study task is a description and explanation of the operational availability parameter. In this task the fundamental mathematical basis for operational availability is developed and its relationship as a part of system's effectiveness is described. Research in this area revealed that application of operational availability as a system parameter varied widely depending on the type of time-critical requirements of the system. Several applications of operational availability to the aerospace system were illustrated to show how the parameter is applied. Emphasis is placed on need for a balanced analytical and pragmatic treatment in the system design process, and tailoring the analysis to best serve each particular problem. Research into the subject showed that past programs tended to overemphasize either the analytical or practical aspects of dealing with operational availability. The result was either a highly analytical "numbers game" that had little credibility, or an overt pragmatic "brute force" approach that tended to overkill or yielded no confidence in being system-effective.

## I. PURPOSE AND SCOPE

The purpose of this study task is to describe the functional activities that collectively constitute the systems engineering technology and discipline required on major aerospace system development programs.

The scope of this document includes systems engineering actions within the definition and design phases of the system development life cycle, and covers the functions of the central systems engineering organizational element as well as systems engineering activities performed by other design disciplines.

## II. DEFINITIONS

| | |
|---|---|
| System | A combination of elements that work together to perform a preconceived mission |
| System Element | Fundamental building blocks that comprise a system, e.g., equipments, facilities, skilled personnel, and procedural data |
| Program Phase | Designation for an increment of a system development used for program control (This term is employed in conjunction with planned baseline management of a system development activity.) |
| Development Phase | Designation of the stages that any system or element of a system goes through in its life cycle, i.e., concept definition and design development production (The program phases may be correlated with the development phase of a system although this is not always the case.) |

| | |
|---|---|
| Design | Activity performed by engineering and scientific skills that transforms requirements into descriptions of equipments, facilities, personnel subsystems, and procedures to implement the system requirements (Design as a generic term encompasses requirements definition concept, design configuration definition, designs, preliminary and final detail design.) |
| Subsystem | A combination of things that make up a major system element that performs a distinct and identifiable function (This is not intended as a general definition of the term.) |
| End Item | Arbitrary designation for portions of a system/equipment for the purpose of system development procurement |
| Criteria | Standards or ground rules established prior to specification preparation that determines requirements for specification and hardware development |

## III. SYSTEMS ENGINEERING TECHNOLOGY

Systems engineering, as a technology, is the collective set of methods, procedures, scientific and engineering skills applied to large and complex system developments to achieve efficient and accurate translation of fundamental mission objectives into a system that best meets the objectives at minimum cost within the required schedule and at minimum risk. The objectives of this engineering technology are to:

1) Assure that the definition of the system or equipment item, to satisfy an established NASA need, are conducted on a total system basis, reflecting hardware, facilities, personnel data, computer programs, and support requirements to achieve required effectiveness at minimum life cycle cost within the required schedule, and at minimum risk;

2) Assure that the engineering effort is fully integrated, so that it reflects adequate and timely consideration of design, test and demonstration, production, operation, and support of the system/equipment;

3) Integrate the design requirements and related efforts of reliability, maintainability, integrated logistics support, human factors engineering, safety, and other engineering specialities with respect to each other as well as into the mainstream of the engineering effort;

4) Assure compatibility of all interfaces within the system, including necessary supporting equipment and facilities; and to assure the compatibility and proper interface of the system with other systems and equipment that will be present in the operational environment;

5) Provide means to establish and control the Work Breakdown Structure (WBS) throughout the life of the system/project;

6) Provide means for evaluation of changes that will reflect consideration of the effect of change on overall system performance and effectiveness, schedule, and cost, and assure that all affected activities participate in the evaluation of changes;

7) Provide a framework of coherent system requirements to serve as source data for development plans, contract work statements, specifications, test plans, design drawings, and other engineering documentation;

8) Provide visibility to measure and judge technical performance status for timely identification of problems;

9) Provide, during the course of the program, requirements for making major technical decisions that optimize the total system to best meet the mission objectives.

Systems engineering is the functional element within the engineering process that applies scientific, engineering, and management techniques to accomplish these objectives.

The implementation of activities to fulfill these objectives is achieved in each phase of the system development cycle by a specific set of functional activities of a systems engineering discipline within the system project organization. The systems engineering discipline performs its function with specific roles and responsibilities that relate to other technical disciplines and to project management.

The problem of achieving these objectives results from the complexity of types of system elements, numbers of specialists, and numbers of organizations (contractors and agencies) involved in a system development. This complex problem is represented in Figure 1 which illustrates the following variables that must be addressed:

1) Evolution of system elements in time;

2) Interrelationship of system elements;

3) Interrelationship of disciplines and organizations of disciplines in each system element definition and design.

For this reason, the systems engineering technology, and the discipline that implements it, is concerned with the process employed to achieve an orderly evolution of the system, and with positive actions within the process to force the definition and design of the best possible system. This process and the functional activities of the system engineering discipline are identified and described in the following section.

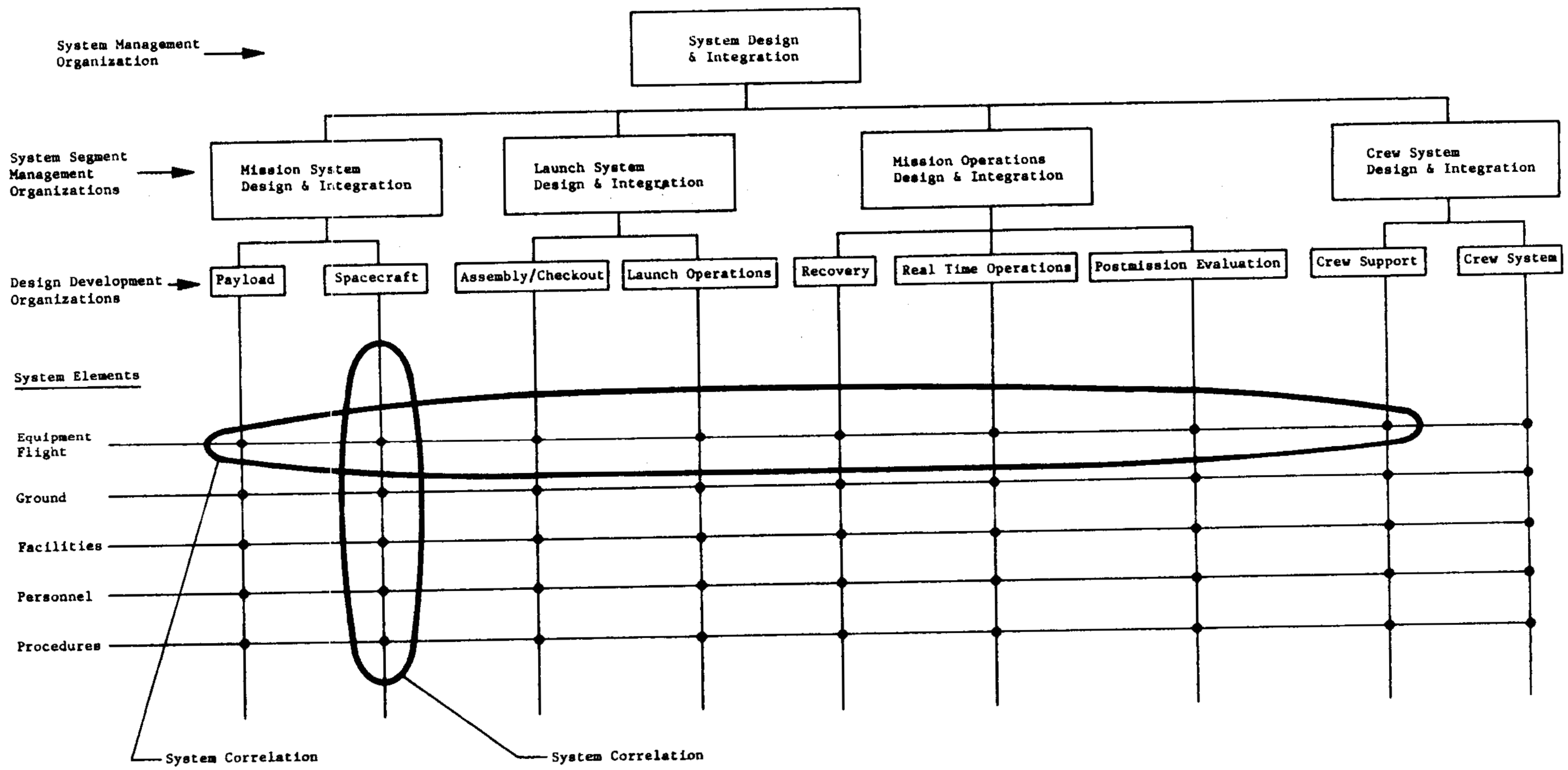



*Figure 1 Organizational Complexity in System Development*

## IV. SYSTEMS ENGINEERING PROCESS

### The Development Cycle

The system development cycle is fundamentally the same whether the system to be developed is a complex aerospace system or a single system element. The development cycle is made up of three major phases of activity--concept, definition, and design.

These phases are natural breakdowns resulting from steps that must be made in transforming an objective into a system of elements. These phases form the basis for the strategy used for program control as covered in NPD7121.1 which establishes the policy for phased project planning.

Within these phases of development, the systems engineering functional activities constitute the means used to force and maintain a consistent, complete, and accurate transformation of mission objectives into a system design.

The concept phase normally consists of analyzing the mission or scientific objective in sufficient detail to develop concepts of implementation. The products of this phase of activity are feasibility analyses, system requirements documentations or specifications, and first-order system development schedules and costs. The definition phase consists of the detail definition of the total system including flight hardware, support equipment, software, personnel, etc. The products of this phase of activity are complete operational use definitions, trade studies, configuration descriptions and preliminary specifications, and plans for the development and use of the system. The design phase consists of the detail design and fabrication of each system element, evaluation of the system through analysis and test, activation of the system, and all other activities required to support and use the system.

Within these development phases, the achievement of desired results is a function of how the overall development process is conducted and positive measures taken within the process to give order to and control the diverse activities of design disciplines.

The system engineering process is a formalized method for planned and scheduled solution of large, complex engineering development design problems. It is based on the scientific method that was developed for solving problems in the physical sciences. This method comprises recognition of the problem, postulating a solution, and then verifying the solution. By extending the scientific method into the domain of technology, a logical process was evolved that enables quicker and more cost-effective solutions to design problems that would ordinarily require several years to resolve.

For the design of an aerospace system, the system engineering process has expanded on the scientific method and extended its use of all aspects of the program. It is used from mission definition through identification of systems performance requirements, design requirements, proposed design solutions, layouts, detailed design, development testing, production, checkout, flight qualification, and mission operation.

The process consists of three steps. Each step is used continuously during the program, first on the initial design and subsequently on all changes to that design. The three steps are (1) definition of requirement, (2) integration of subsystem design, and (3) verification of subsystem performance to the design requirements.

The objective of this process is to produce a system design that will satisfy all mission requirements with a minimum expenditure of program resources.

The first step of the system engineering process occurs in the concept phase. The feasibility of the object mission is determined and the fundamental system concept is selected. In the definition phase of the system engineering process, the object mission is specified, and, from it, mission objectives and system performance requirements are derived. The Statement of Work (SOW) incorporates these requirements and further identifies performance requirements for all subsystems. These requirements are defined in a mission/system requirements document. Design requirements based on reliability, environment, safety, service life, and other considerations are identified in an environmental and design requirements document.

Ground support equipment (GSE) requirements for the system evolve in a similar manner, originating from mission/system requirements.

Requirements that must be considered in the overall system design may be grouped into three major areas which are performance, design, and test. Within each of the major areas a representative list of requirements may be tabulated. This tabulation, in the form of a list, has been compiled and is given in Table 1. From the length of this list it can be seen that the definition of all requirements that constrain the system design cannot be completed prior to initial design release and, therefore, a design change system is required to revise released drawings and specifications. It will also be noted that because of the low level of requirements shown, such as performance requirements at the component level, not all requirements can be known initially. These requirements evolve as the design progresses.

Systems analysis of all the requirements illustrated by Table 1 results in the second step of the systems engineering process. Tradeoff study reports that identify alternative mechanizations, satisfy the requirements, and select the best design are performed. These reports also describe how the system was sized, the performance envelope of the complete system in its operating environment under all static and dynamic variations of external inputs and internal system tolerances, critical interactions with or dependence upon other systems or structures, safety precautions, provisions for reliability, producibility, and maintainability system growth considerations, and unusual human factors aspects in the design. The results of these analyses culminate in a configuration baseline that is the first definition of a complete system configuration. Design layouts, specification control drawings, process specifications, and procurement specifications proceed from this document to define the configuration exactly and govern its procurement, manufacture, assembly, test, and checkout throughout the design, development, and production process.

As the design takes specific form, the requirements documents progressively "harden" to the form of performance, design, and test requirements for the hardware. These are incorporated in system, system element and subsystem specifications that describe specific design and verification requirements for the detail design of the system (Part I). Part II of these specifications is the documented solution to the Part I specification. The solution originates during the design of system elements and specifies product configuration, and all verification, preparation for shipment, and use instructions.

A similar hardening of requirements occurs simultaneously with GSE and culminates in a ground system specifications, GSE and item specification, and support equipment specifications.

*Table 1 Typical Requirements for Aerospace Systems*

## I. PERFORMANCE REQUIREMENTS

### A. SYSTEM

- Mission Objectives
  - Mandatory
  - Desired
- Mission Profile
  - Normal (reference)
  - Alternative
  - Abort
- Mission Trajectory
  - Position
  - Attitude
  - Velocity
  - Acceleration
- Payload
- Crew
- Timeline
- Environment
  - Natural
  - Induced
- Interfacing Vehicles

### B. SYSTEM ELEMENTS

- Primary Functions
- Alternative Functions
- Emergency Functions
- Duty Cycles
- Tolerances and Error Budgets
- Interfacing Systems and Subsystems
  - Inputs
  - Outputs
  - GSE
  - Facility
  - Associate Contractor
  - GFE

### C. COMPONENTS

- Primary Functions
- Alternative Functions
- Emergency Functions
- Duty Cycles
- Power Consumption
- Switching and Sequencing Logic
- Environment
- Cooling and Heating
- Lubrication
- Consumables
  - Solids
  - Liquids
  - Gases
- Tolerances and Drift Rates
- Size, Shape, Location
- Mass, e.g., Moments of Inertia
- Loads
  - Static
  - Dynamic
    - Acceleration
    - Vibration
    - Acoustic
    - Shock
- Failure Rate
- Safety Margin
- Useful Life
- Aging
- Humidity
- Radiation
  - Electromagnetic
  - Radio Frequency
  - Nuclear
- Biological and Chemical
  - Life Support
  - Human Performance
  - Moisture and Fungus
  - Contamination
  - Corrosion
  - Cleanliness
- Safety
  - Ground
  - Flight
  - Personnel
  - Equipment
- Performance Growth Capability
- Interfacing Components
  - Mechanical
  - Electrical
  - Fluid
  - Structural
  - Environmental
  - Radiation

## II. DESIGN REQUIREMENTS

### A. DESIGN AND DEVELOPMENT

- Contract Specifications
- Design Standards
  - Government Specifications
  - Standards Drawings
  - Drawing Requirements Manual
  - Design Manual
  - Material Manual
  - Identification and Marking Manual
  - Standard Shapes Manual
  - Electrical/Electronic Manual
  - Fluid Systems Manual
  - Mechanical Parts Manual
  - Structures Manual
  - Master Dimension Specification Manual
  - Design Cost Guide
  - System Safety Design Standard Manual
  - System Safety Operations Standards Manual
  - Standard Practice
- Legal
  - Security
  - Codes
    - Civil
    - Structural
    - Architectural
- Mockup Inspection Results
- Management Reviews
- Design Reviews
  - PRR
  - PDR
  - CDR
  - FRR

### B. PRODUCTION

- Program Schedules
- Program Costs
- Producibility
  - Manufacture
  - Assembly
  - Installation
- Interchangeability
- Workmanship
- Identification and Marking
- Acceptance Test Results
- Systems Servicing
- Systems Checkout
  - Individual
  - Combined

### C. MISSION SUPPORT

- Logistics
  - Sparing
  - Maintainability
    - Maintenance
    - Maintenance Repair Cycle
    - Service and Access
  - Replaceability
    - Ground
    - Inflight
- Transportability
  - Preservation
  - Packaging
  - Packing
  - Handling
  - Shipment
  - Storage
- Orbital Support

### D. PRELAUNCH INSPECTION TEST RESULTS

- Environmental
- Leak and Functional
- Static Firing
- Electrical Mating
- Flight Readiness
- Countdown Demonstration

### E. FLIGHT TEST RESULTS

### F. POSTFLIGHT INSPECTION RESULTS

## III. TEST REQUIREMENTS

### A. TEST

- Test Plan
- Test Procedure
  - Test Objectives
  - Test Purpose
  - Configuration
  - Simulation
  - Measurements
  - Accuracy
  - Statistical Design
  - Criteria for Success
  - Criteria for Failure
- Test Results
  - Breadboards
  - Prototypes
  - Verification
  - Major Ground Development
    - Structural
    - Environmental
    - Propulsion
- Major Flight Development
  - Launch Environment
  - Orbital
  - Atmospheric Entry
  - Recovery

Requirements reviews follow requirements definition for all systems and facilities and they initiate Phase II, the integration phase of system engineering. These reviews use standard operations analysis techniques to fly the mission on paper using the proposed designs and computer simulations of the nominal and abort trajectories to determine mission success and crew safety probabilities, to verify system compatibility with mission objectives, and to improve the total design. Simultaneously with the reviews, integration of the design proceeds as integrated schematics are completed to assure continuity, compatibility, and responsibility of subsystem-subsystem interfaces, subsystem-GSE interfaces, and GSE-facility interfaces.

When approximately 10% of the basic detail design process has been completed, the preliminary design review (PDR) is held. This is an assessment of the preliminary design of all flight, ground, and test site subsystems for compatibility with mission objectives, and is a continuation of the integration phase begun with the requirement reviews. Before completion of production drawing and design specification release, a critical design review (CDR) of all flight and ground hardware is completed. The purpose of this review is the same as for the PDR except that it is more thorough, particularly insofar as equipment interfaces are concerned, since much more data are available. After the action items have been worked, the basic release is completed.

The third step of the system engineering process commences with verification analysis studies and continues through all subsequent testing including development, qualification, acceptance, checkout and mission operations. Performance verification for all components and subsystems is achieved through analysis of test. Verification results permit a technical performance evaluation of the design and, if the results are favorable, increasing confidence in the reliability of the equipment. Verification is achieved by comparing results with specification requirements.

Through a continuous iteration of systems engineering phases--requirements, integration, and verification-- an effective design will be produced with a minimum cost and time expenditure. Requirements are documented and traceable to the design for use at reviews and for evaluation of proposed changes. Technical progress of the development is monitored, assessed, and displayed to give precise status of progress and to pinpoint areas that require additional resources to improve progress.

These process activities must be reflected in specific functional activities in each phase of development. They can be categorized as analytical, integration and engineering actions in each phase of system development. The aggregate of these functional activities constitutes the systems engineering disciplines roles and responsibilities.

## V. SYSTEMS ENGINEERING DISCIPLINE

The systems engineering discipline is the technical organizational element that provides the skilled resources, methods, and procedures to achieve complete and optimum system objectives with the resources available. The functions, roles, and responsibilities fall into two categories: those that make up a central systems engineering discipline and those that fall within the technical discipline organizations that participate in the system development. These two types of systems engineering activities are shown in Figure 2.

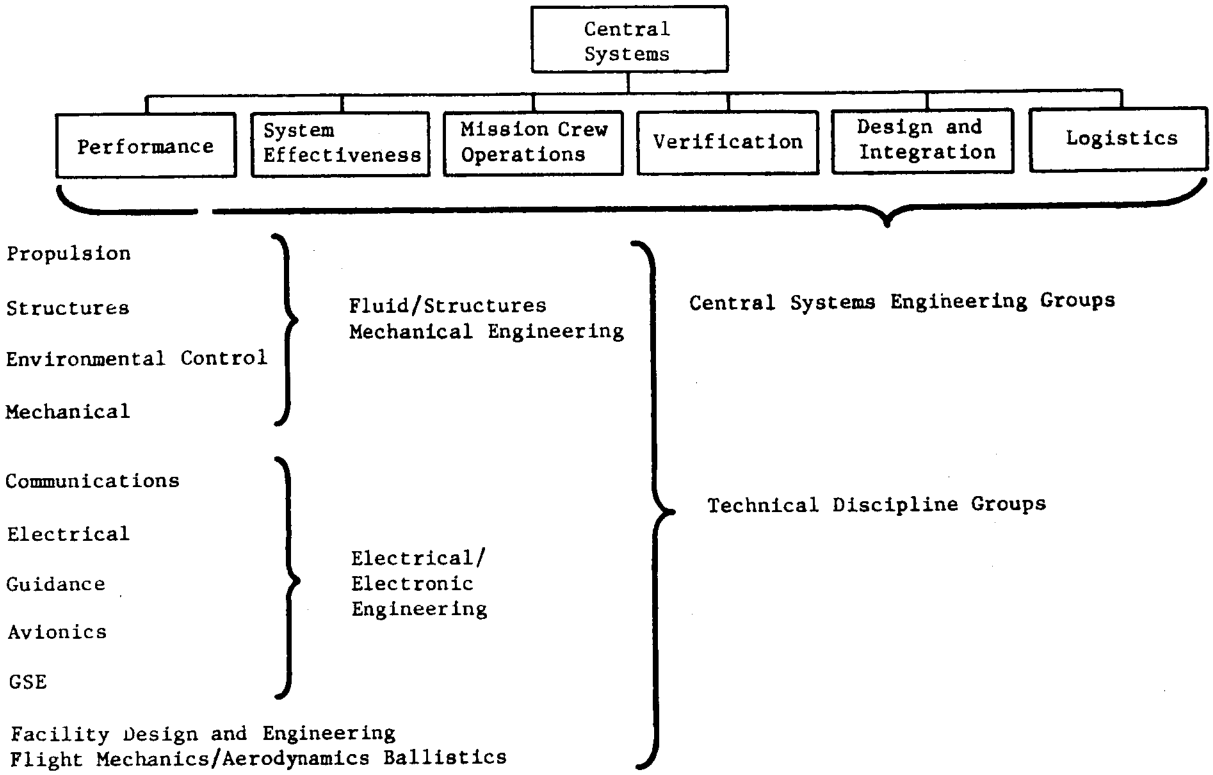



*Figure 2 Systems Engineering Organization*

## A. CENTRAL SYSTEMS ENGINEERING DISCIPLINE

The objective and purpose of a central systems organization is to make available to development project management skilled resources, methods, and techniques to solve problems exhibited by complex systems in each phase of development. The functional activities of this discipline are (1) those that are directed at making the technical development process an efficient and controlled operation, and (2) those specific line activities within the development process. The first of these management activities govern and control the actions of all disciplines and all system elements in the technical development of the system; the second is the requirements definition, integration, and verifications performed as a part of the system development. These activities and the functions that are performed are described in the following paragraphs.

### a. System Management Activities

The part played by the central systems discipline in the direction and control of a system development is to establish the central requirements and constraints that govern each system element, provide the necessary decision criteria and techniques for deciding between alternatives and providing the mechanism for evaluation of results during and at the end of the phase effort. The description of these three functions follows.

#### 1. Baseline Control

Within and between development phases, the systems engineering activity required to achieve consistent and compatible results is to establish control over the activities of all organizations and disciplines engaged in the system development.

The fundamental approach is to establish and maintain a system of positive definition, documentation, and control between interfacing requirements, design requirements, and design solutions. The heart of this approach is the system engineering process and baseline management.

Baseline management is a technique that uses uniform documentation, engineering reviews, and standard procedures to ensure an orderly transition from one major commitment point to the next in the system engineering process. Baselines may be established at any point in a program where it is necessary to define a formal departure point for control of future changes in performance and design.

Systems engineering establishes the documentation complex in the form of specifications, interface controls, and other requirements data forms in each phase, and maintains them as control reference points during the evaluation of the design in each phase. Since the development of a system is an iterative process, continuing changes and revisions in requirements are necessary to achieve a balanced design that yields the most benefits. The progressive baselines established through the development cycle provide the means for assuring these revisions are made under controlled conditions. Systems engineering examines these revisions against the baseline for impact on the system's ability to perform the mission. This activity provides continuing assurance that the integrity of the system/mission relationship is maintained.

2. Decision Management

The development of complex systems in which many different and conflicting requirements are present requires that a means be provided for relating characteristics of the system in terms that permit them to be combined, and the value to the total system assessed. In each phase of the development cycle, trade studies are made between alternative approaches, concepts and designs with the objectives of selecting the candidate having the greatest overall benefit to the sytem, i.e., the one striking the best balance or compromise between all mission/system requirements and program constraints. Since these decisions occur within each system element, and are performed by the technical disciplines within a broad organizational complex, a consistent means in terms of decision criteria and methodology is required.

Systems engineering develops the priority, ranking, and relative values of program, mission, and system parameters to facilitate selection between candidate concepts, configurations, and designs. In addition, guidelines are provided for the format and content of trade studies to assure complete treatment of each major decision. System engineering provides assistance in the conduct of these decision actions and approves results of the study prior to project management's final approval.

3. Technical Evaluation

In each program phase, systems engineering performs an assessment of the technical results on a continuing basis and at predetermined points in the process to assure that the consistency, completeness, and integration of all system elements is maintained. The objective of this activity is to find problems (performance and design) early enough to avoid significant cost and schedule impact. This objective is accomplished by tracking the performance and design, and maintaining an overall system visibility to performance capability, design characteristics, interfaces, and configurations.

Systems engineering provides tracking methods and techniques, and establishes reviews and review procedures to examine development results, identify discrepancies, and follow-up on their resolution. The tracking and assessment of performance is accomplished by developing and maintaining cognizance over the primary performance factors of the system, and comparing them to the allocated requirements. Reviews are accomplished by identifying appropriate times in the process based on critical decision points or program requirements for a baseline update, assembling a team of specialists who are knowledgeable in the design and technologies involved, and in performing an indepth examination and comparison with baseline requirements.

4. Summary

The central systems engineering provides resources for and accomplishes the following system process activities during each phase of system development:

1) Requirements

   a) Define specification mechanism (hierarchy of requirements documents to be used to implement the system definition).

   b) Compile, integrate, and issue initial requirements for each program phase.

   c) Perform baseline requirements management during each development phase.

   d) Compile results of each phase into specifications for the next phase activity.

   e) Develop WBS and SOW requirements.

2) Decision Requirements

   a) Develop and provide decision criteria for combining mission, system, and program factors in making decisions between alternative approaches, concepts, and designs.

b) Provide standards of format and content of trade studies.

c) Assist in performing trade studies that have significant system impact.

3) Technical Evaluation

a) Plan, organize, conduct, and follow up system design review.

b) Develop techniques for and perform technical performance tracking.

b. <u>Central System Engineering Line Functional Activities</u>

The central systems engineering discipline is composed of five principal elements and one correlated element as follows:

1) System Design and Integration

2) System Effectiveness

a) Reliability

b) Maintainability

c) System Availability

d) System Safety

e) Environmental Requirements

3) System Verification

a) Design Verification

b) Premission Verification

c) Mission Verification

d) Postmission Verification

4) Mission/Crew Operations

5) System Performance

6) Logistics (Correlated)

These organizational elements represent the basic system and mission attributes desired as final results from the system development process. These factors have a broad effect on all system elements that comprise the total system. This is illustrated in Figure 3. As shown, these systems engineering disciplines are involved in all possible types of system elements.

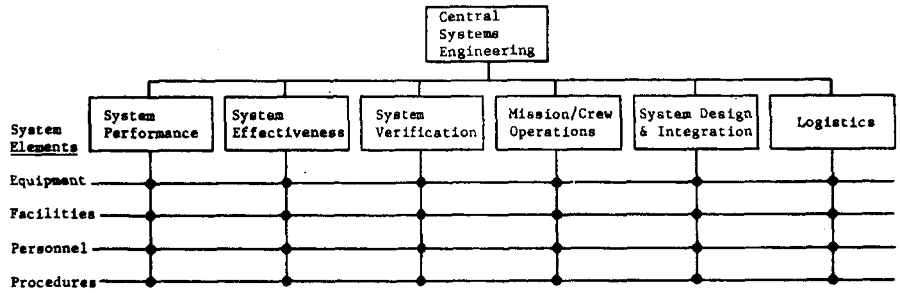



*Figure 3 Central Systems Engineering Desciplines/System Element Matrix*

The roles and responsibilities for functional activities of each of these disciplines is related to the fundamental design process in any system element development. Figure 4 shows this fundamental process together with the type of activities performed by systems engineering.

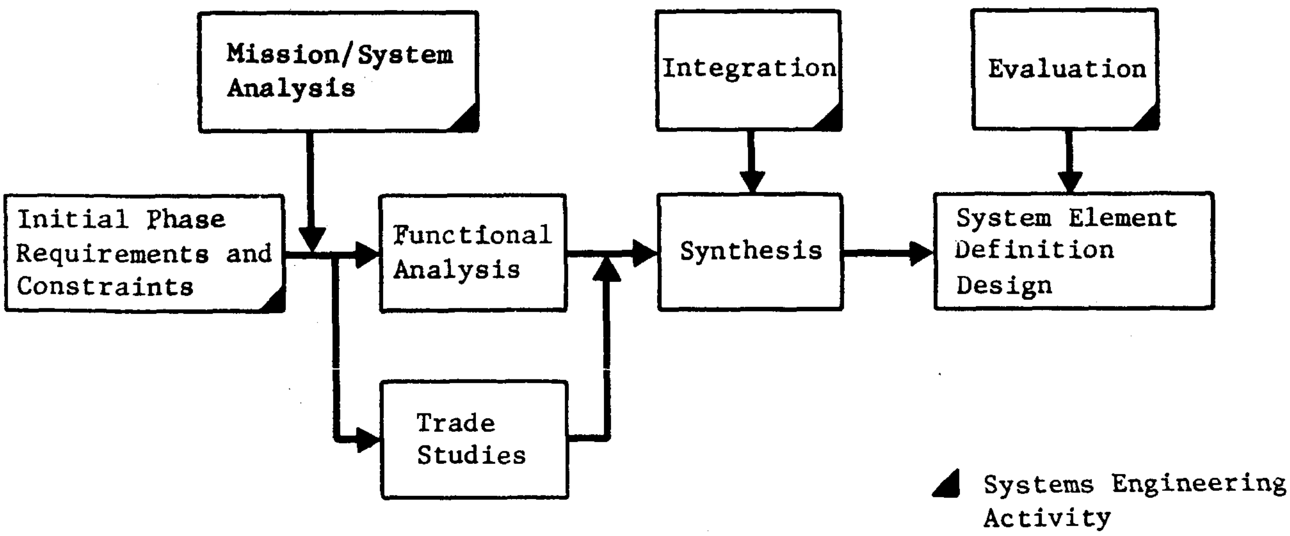



*Figure 4 Fundamental Design Process*

Systems engineering provides initial design concepts and analysis, performs integration between system elements and finally evaluates the output results for compatibility. These actions are the same for each program phase and for all system elements. Each of the design disciplines, and the systems engineering activities involved in each, are described in the following subparagraphs.

1. Systems Analysis and Criteria

The initial steps in the development process for system definition are activities identified as systems engineering functions. These activities, shown in Figure 22, page 115, represent the initial mission, program, and systems analyses necessary to provide consistent criteria from which the definition of individual system elements can proceed. Central systems engineering has the lead role in these activities. It will be noted that among the inputs to these functions is the conceptual design activity of the previous phase and the applicable study guidelines provided by the conceptual design activity. The first of these is the studies, analyses, and analytical tools developed by the study team during the concept study phase. The study guidelines are the directive data provided to all competing teams as a reference set of ground rules and requirements to govern the design definition. These data constitute initial conditions for the development problem. The first step is to state the problem based on what is known, and to expand these initial conditions sufficiently to enable the development of each system element to proceed along complimentary lines. The subsequent development activities are highly iterative and the object of establishing directive criteria is to start these activities with guidance so as to minimize the number of iterations and assure that a common starting point is used by all specialty groups. Many groups contribute to the development of these baseline requirements. The systems engineering discipline compiles these data and issues a requirements document that becomes directive to all products (subsystems) and functional (vehicle performance, reliability, safety, logistics, etc.) disciplines.

The content of this document is shown in the Appendix. The extent of these requirements is dependent on the depth of study during the previous phase. The approach used is to provide the best data possible at the start of the study and to add and revise the requirements as the definition proceeds.

## 2. System Performance

In the system design and integration of a complex aerospace system, control and management of flight equipment performance is a major concern. In each type of system element (launch vehicle, spacecraft and payloads), performance capability, together with safety, reliability, and availability are the primary factors in mission success. The objective of systems engineering is to provide the means for controlling, from the total system point of view, the system performance capability. This involves determining and controlling all factors that may influence system performance capability, such as mass properties of the system, flight dynamics, guidance, software, etc. One major element of controlling system performance is managing system mass properties that are influenced by all flight system elements. The following is typical of how this is done and representative of how other areas would be controlled.

The system performance group provides skills and methods for allocating estimating, predicting, and measuring weight and other mass properties characteristics in all phases of development. Again, as in all central systems activities, the approach is establishment of a baseline of allocated requirements, participation in decisions as the design evolves, and assessment of results at the end of each phase of compliance with requirements.

Initially critical mass properties are defined and related to the vehicle system performance. They are subsequently documented in specification, interface, and requirements trees to be used ultimately as the primary reference for demonstration of delivered performance.

This set of design requirements is then broken down by design function and assigned to the responsible personnel for effective control. Other forms of control involve implementing subcontractor weight cost incentive plans, establishing the value of a pound (in the performance sense) so as to influence tradeoff decisions, and dissemination of a timely mass properties status from which decisions regarding corrective action can be based.

The analysis of mass properties characteristics begins with preliminary design criteria and a concept formulation from which a first weight estimate is derived. Subsequent iterations during design definition evolve more refined design mass properties. Predicting performance oriented mass properties continues through the design and build process with a constant awareness of their effects on required system performance. The mass properties analysis is not complete until proper allowances have been made for the lack of detail design, contingencies, and historically proven weight growth.

Mass properties analysis data whether a first cut estimate or a refined analysis are accompanied by a confidence level that requires constant assessment. The control of mass properties in support of delivering system performance requires supporting analysis and historical experience developed in a timely manner to maximize the data confidence level.

The data confidence level continues to improve as hardware items are weighed and accounted for in a prefinal assembly stages of development. This leads to the last stages of data development that include final delivered vehicle mass properties verification by measurement/analysis plus any required steps to accurately track vehicle configuration and associated mass properties up to flight time and on through the mission.

To assure delivery of effective mass properties/system performance, several prerequisites must be recognized. First of all, consistent design definition and data breakdown help significantly in using the data. Next, program awareness and preparedness to respond to required design influenced by critical mass properties must have a high priority. Also, analytical methods and measurement equipment required to provide good data results must be consistent with data accuracy requirements.

System performance will be delivered only after the close association of management action, thorough data acquisition, and factual data dissemination influence the required design decisions.

Central systems mass properties serves as a member of the system performance team (flight mechanics, propulsion, guidance, etc) and assists in the sizing, evaluation, and trade studies in the synthesis of a performance/design solution. In summary, systems engineering performs the following activities to control mass properties that affect flight vehicle performance.

1) Initiate and maintain a system to provide a high degree of weight and mass properties control of flight articles.

2) Provide critical mass properties for input to contractual documentation, specifications, and program control documentation.

3) Establish mass properties allowances, monitor and control detail design weight, and assist in establishing flight configuration.

4) Determine and be responsible for product weight, center of gravity balance, moment of inertia and product of inertia by using standard methods of estimation, calculation, and actual measurement.

5) Maintain mass property accountability, prepare and issue reports reflecting program weight status and performance mass properties data.

6) Supply and coordinate flight weight and mass properties summaries for the purpose of analyzing product performance.

7) Determine and verify weight of components and flight (airborne) articles by actual measurement.

8) Provide field weight liaison for the purpose of flight configuration accountability prior to product flight.

9) Participate in flight performance analysis and sizing, provide weight estimates, and develop allocations for system definition.

10) Develop mass properties management plans.

11) During definition/design perform mass properties trend analysis and prediction.

12) Maintain cognizance of mass properties requirements standards.

13) Develop and provide monitoring and control over payload dependent elements (stowage, consumables).

3. System Effectiveness

System effectiveness analysis provides the skills, methods, and procedures for system optimization, safety availability/dependability, and environmental requirements. The objective of system effectiveness analysis is to provide means for measuring, allocating, and selecting designs and approaches that yield the maximum probability of mission success, under the risks assumed. The function or measure that determines quantitatively the achievement of the optimal combination of resources is a "principal figure of merit".

This criteria may be in the form of cost figures, or the specification of technical performance characteristics. A system may have several principal figures of merit, and the resultant outcome combined to furnish one overall measure. In general, a systems effectiveness analysis isolates the critical accountable factors in terms of a value tradeoff between significant factors. The basic elements of a systems effectiveness analysis include:

an assessment of the state of the art to define constraints on solutions limited by technology, risk, and time;

an assessment of the critical and most sensitive design and performance parameters to determine the necessity for further refinements;

preliminary design configuration of potential and hypothetical alternatives;

design tradeoff investigations;

system description and parameter specifications.

*Optimization* - Optimization refers to attainment of the "best" combination of resources in accordance with selected criteria. It represents an attempt to quantify the factors (measured in terms of cost, or technical performance) in order to select from a set of alternatives. Since a system may have associated with it multiple principal figures of merit, the specification of more than one analysis model may be required for each feasible configuration or design approach. For example, in a multistage decision problem, dynamic programming may be used to optimize the totality of overall system combinations. However, at each stage in the decision process, the technique of maximum likelihood estimation may be used to obtain parametric data for use with other subsequent optimization models. In any event, the degree and analysis of functional areas that determine the parameters to be optimized include:

environmental factors;

reliability and maintainability;

support policies;

numbers of skill levels of personnel;

training equipment and facilities;

logistic considerations;

operational modes;

interfaces with other system/subsystems.

In addition, all pertinent assumptions made at each phase in the analysis must be stated explicitly. For example, the relationship between logistics and repair time, as well as the assumptions of failure rates and repair time, must be adequately documented, and the rationale and data source identified.

*Application of System Effectiveness Analysis to Engineering Design* - Design optimization deals with application of systems effectiveness techniques to determine the best system configuration in terms of performance characteristics and cost. This involves the establishment of criteria or models for selecting among alternatives such that the evaluation of different missions, modes of operation, and system design concepts, etc can be analyzed within a common frame of reference. System effectiveness models are usually developed early in the system definition phase to provide the means for quantitatively combining system performance parameters having different dimensions with system cost, to arrive at an overall figure of merit is an expression of the effectiveness of the design approach, and as such can be used to compare the composite attributes of one design approach with another. System effectiveness models allow the input parameters to be varied individually so that their relative sensitivity on total system performance and life cycle costs can be determined. Parameters used in the effectiveness models correlate system functions and system elements. The optimization analysis is performed primarily during the system definition phase when optimization is applied to the allocation of specific requirements, for performance of equipment, facilities, personnel skills, computer programs, and other software, in conjunction with a comprehensive analysis of mission, support, and operations requirements, and of total cost of the system. This optimization stresses consideration and integration of all technical disciplines such as reliability, maintainability, safety, etc. Expected technical performance results are the optimized combination of contributions from all engineering specialties whose parameters are factors affecting performance and cost.

The functional activities involving design optimization and system effectiveness investigations use the techniques and disciplines of systems analysis. Typically, these consist of --

1) Parametric Analysis Methods,

2) Search Methods,

3) Methods of Steepest Ascent,

4) Game Theory,

5) Statistical Methods,

6) Scheduling Algorithms,

7) Stochastic Processes,

8) Linear Programming,

9) Dynamic Programming,

10) Geometric Programming,

11) Simulation,

12) Monte Carlo Techniques,

13) Network Methods.

Of these methods, Parametric Analyses as applied to the selection of design parameters which maximize system performance, are the most widely used of the various techniques in systems analysis. This is perhaps because these methods are the best understood and are simplest to apply.

Generally, Parametric Analyses consist of the following steps:

1) Define a baseline (or preliminary) design using analyses of system mission objectives and requirements.

2) Develop functional relationships between system parameters and achievement of objectives (i.e., outage and payload in orbit).

3) Vary the system parameters one at a time over a feasible range and measure the effect on achievement of system objectives. (This is usually plotted to add visability and the parameter value selected at that value which maximizes the achieved objectives.)

4) With the parameters thus selected, measure the effect of the combination set of parameters on total objectives achieved.

The first two steps of this process are common to all approaches relative to selection of optimum parameters. The preliminary design may be based on parameter analyses of subsystems and/or components included in them. The preliminary design serves as a reference to measure changes in performance with respect to achieved objectives.

Some obvious problems can be encountered in this process, and engineering judgments are usually exercised to avoid these. For example, weight, volume, and power constraints could be exceeded unless some prior allocation of these resources to subsystems and assemblies is made. Some functions will be monotonically increasing or decreasing over the feasible range for the design parameter; other problems that are not so easily solved are the interactions between such parameters as thermal environment and electrical power. These must be evaluated independently in an iteration process.

In summary then, some of the functional activities of the design optimization procedure (using systems analysis methodologies previously mentioned) are:

1) system effectiveness analysis;

2) availability/dependability specification;

3) optimal policy structure for maintainability, logistics, and supply;

4) development and provision of methods of cost effectiveness analysis;

5) parameter sensitivity analysis;

6) technological forecasting;

7) risk assessment;

8) evaluation models.

*System Safety* - System safety engineering is concerned with reducing hazards and failures by influencing system definition and design to achieve acceptable risks in each mission state. The sequence of events in system safety is:

1) mission analyses and identification of hazards;

2) definition of criteria or requirements for all system element definition/design;

3) provision of safety inputs to system element trade studies;

4) analysis of system element definition/design to determine compliance with requirements and to uncover hazards;

5) identification and follow-up on solutions (design changes or procedural changes).

To maximize safety, it is necessary to identify and minimize those failures that produce the unsafe condition failures. It is also necessary to identify the warning time associated with failure, the feasibility and method of detection, and the corrective action required, particularly that which will minimize crew risk. Safety Analysis starts in the conceptual phase by reviewing or establishing mission ground rules and assumptions. A ground rule such as fail-operational/fail-safe versus fail-operational/fail-operational/fail-safe has significant impact on design, operations, and cost. Mission ground rules are refined and updated until the equivalent of a mission flight plan is generated. This technique permits the systems analysis and trade studies to consider current mission planning. As system definition proceeds, definitive design oriented criteria are developed. A design safety handbook is invoked to provide a reference to safety design criteria that can be used for evaluation of quantification approaches. Crew Safety Analysis is of necessity reiterative and the analytical technique requires assessing the impact of equipment changes throughout the life of a program.

Crew Safety Analysis involves not only all design areas, but must use and understand reliability, maintainability, human factors, on-orbit mechanics, environmental, etc data to assure that the inherent crew safety is not degraded during the build, test, change cycle, and operational phases of a program. When the crew is identified, crew safety personnel become the focal point to work specific detailed requirements, simulations, changes, and procedures.

In summary, the system safety tasks performed in the definition/design phases are:

1) Prepare system safety engineering plans.

2) Specify general requirements documents to be used in the system definition/design; e.g., MIL specification, NASA documents, safety handbooks.

3) Perform failure hazard effects analysis for crew/system safety.

4) Establish hardware and software requirements for detecting safety significant malfunctions.

5) Perform warning time analysis.

6) Perform abort/escape system studies to verify system design and develop new design requirements.

7) Provide design criteria for safety critical areas.

8) Perform hazard analyses for each mission state and each system element.

9) Identify range requirements and obtain waivers when necessary.

10) Identify procedural constraints necessary to assure safety.

11) Participate in development and use of simulators as necessary for safety purposes.

12) Perform human error analysis, identify potential flight crew and ground command errors that can have safety impact.

13) Participate in safety working groups.

14) Participate in and/or conduct design reviews of hardware as necessary for safety.

*Availability/Dependability* - The steps involved in sizing and optimization of availability/dependability involve a series of analyses as shown in Figure 5, and are aimed at sizing reliability and maintenance requirements that drive the mission and support system designs. The disciplines directly involved in these activities are reliability and maintainability specialists. As shown in Figure 5, availability/dependability requirements result from mission analysis in which the mission success requirements are identified. This analysis includes the definition of mission requirements and system configuration and definition of probability requirements for system definition and design. Operational analyses of the system and its operational

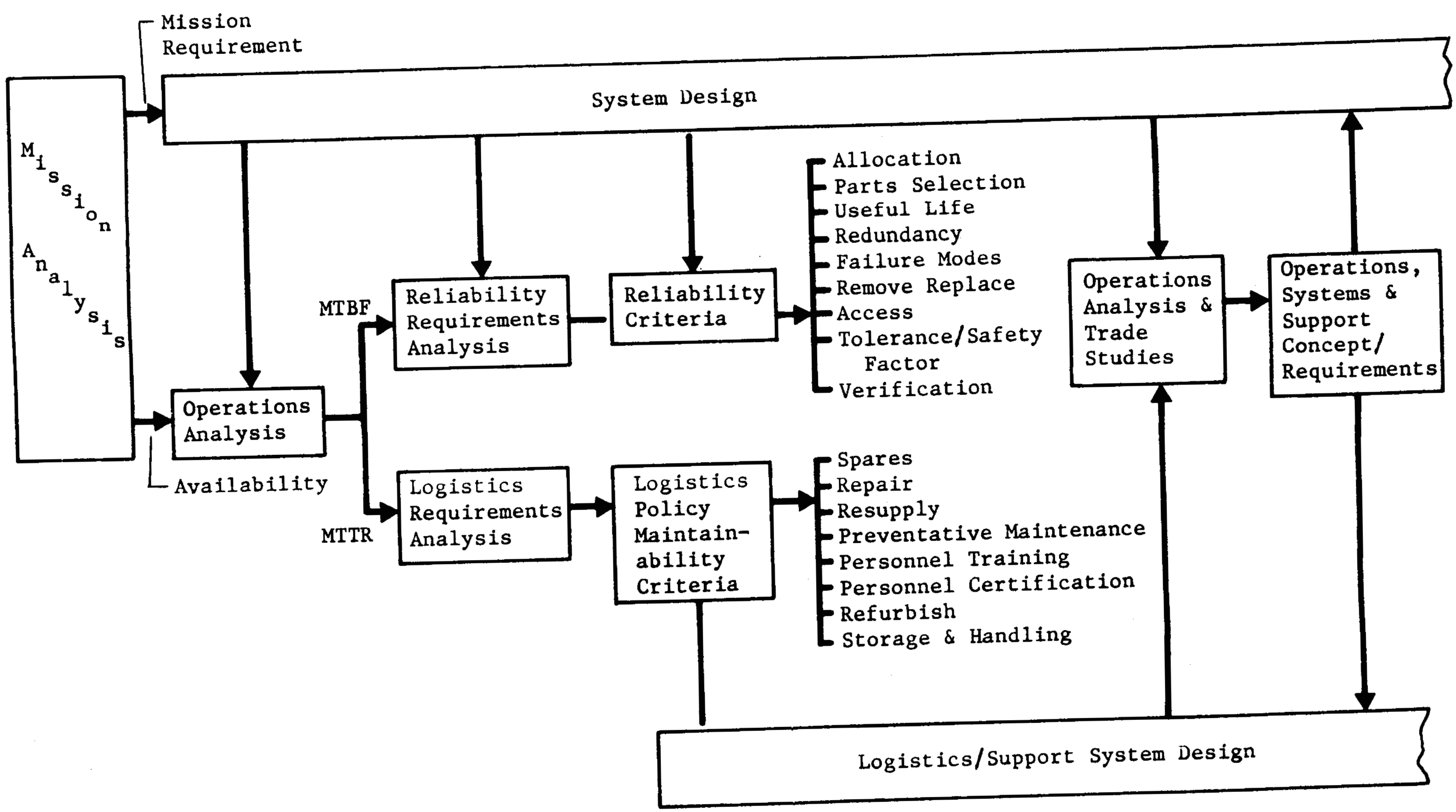



*Figure 5  System Design Disciplines, Criteria, and Functional Elements*

concepts result in MTFB (mean time between failure) and MTTR (mean time to repair) requirements. These became the requirements that led to a reliability and maintainability policy which drives the mission system and support system designs. These analyses are performed by system analysis, reliability, and maintainability specialists in conjunction with system design and logistics engineers. The parameters involved in the analyses and requirements definition are shown in Figure 6.

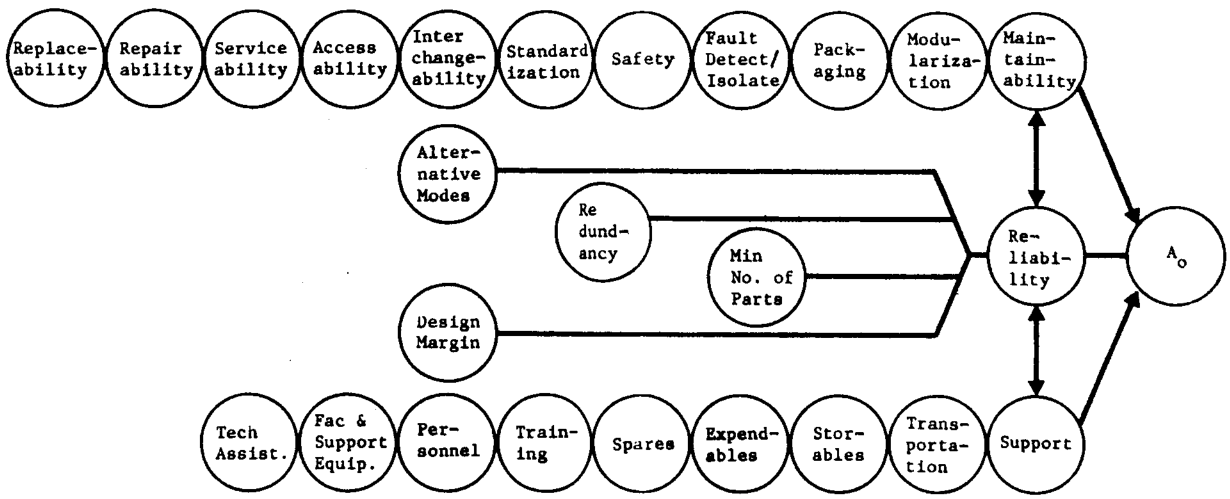



*Figure 6 Maintainability/Reliability/Support Parameters*

In the capacity of a system technical parameter, maintainability (M) is a characteristic of design, qualitatively and/or quantitatively expressed (Fig. 7), that enables timely and economical accomplishment of system maintenance and logistics support. This implies that some level of maintainability characteristics or features can be defined, and applied to the system development processes in the manner of a design constraint. The level of maintainability necessary for any given system is directly related to defined system operational requirements and support concepts and system constraints typified by complexity, operational cost, and time criticality. (Time criticality as used here applied to systems that are launch-window critical, ground-turnaround-cycle critical, launch-countdown critical, etc.) Figure 8 illustrates the interrelationship of such program elements.

Maintainability, as a technical parameter, is used to assess the support impact of prospective design approaches (a tradeoff-analysis function), as well as establish maintainability requirements for design compliance. In the role of a tradeoff factor, maintainability analysis is performed to establish factors such as maintenance/man-hour costs, support materials costs, shop and depot hardware turn-around costs, operational-site manning costs, personnel training costs, operational downtime necessitated by maintenance requirements, and reaction times for emergency maintenance. Factors such as these are instrumental to overall program determinations of numbers of vehicles, types, and numbers of depot facilities/services, crossover use of site personnel, launch-on-time probabilities, etc. In the performance of such analyses, parametric-elements of maintainability are closely reviewed to establish effects, impact of the effects upon system configuration, and alternative design incorporation approaches. These parametric elements include repairability, replaceability, serviceability, accessibility, interchangeability, standardization, safety, fault isolation and checkout, packaging, and modularization.

| QUALITATIVE | QUANTITATIVE |
|---|---|
| "The control thruster assembly shall be designed for integrated line removal/replacement actions, using quick-release mounting hardware, flange-mounted fluid connection points, and plug-type electrical connections." | "The control thruster assembly shall be designed such that the mean active corrective maintenance time ($M_{ct}$) required to effect line replacement shall not exceed 1.0 hour." |

*Figure 7 Maintainability Characteristic Expressions (examples)*

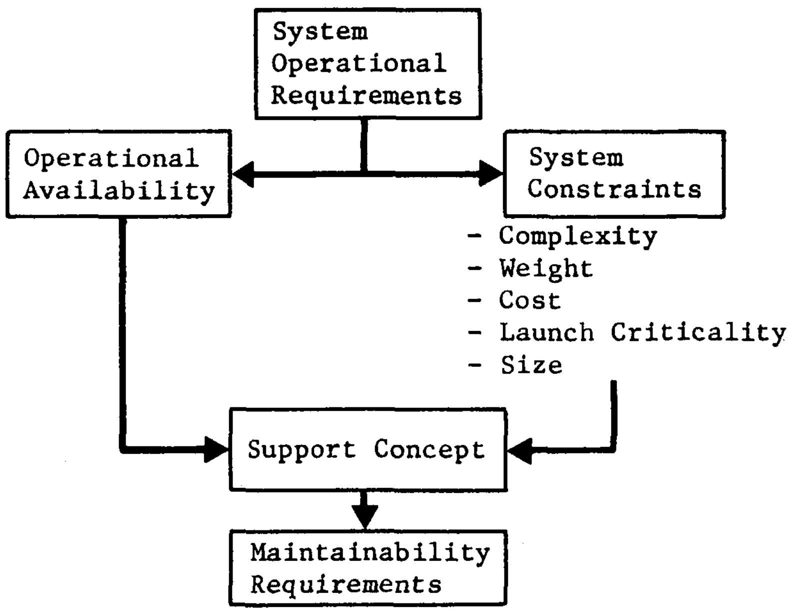



*Figure 8 Basis for Maintainability Requirements*

In the capacity of a development program function, maintainability works in an interfacing manner with other engineering and support functions (e.g., reliability, safety, quality, maintenance engineering, and logistics) to produce/update checklists, criteria, design review reports, maintenance verification and demonstration results, etc. As implied by available standards and handbooks, maintainability functional activities occur in a waterfall fashion throughout the system lifespan.

In summary, maintainability functional activities consist of the following steps:

1) Define the maintenance concept.

2) During conceptual and definition phases, define functional roles of logistics and maintenance programs during development and operational program phases.

3) Prepare maintainability program plans.

4) Establish maintainability design criteria consisting of qualitative design features and quantitative design time goals.

5) Perform tradeoffs, make design recommendations, and assist designers to implement maintenance requirements.

6) Perform quantitative task predictions of design inherent maintainability.

7) Provide maintainability program technical coordination.

8) Perform maintainability integration between system element/ organization elements.

*Environmental Requirements* - As in other functions in central systems engineering, definition and control of environmental requirements is an activity aimed at achieving consistent and complete results that best meet the mission requirements. The environments that have a significant bearing on the successful definition and design of a system are --

1) natural environments that affect the system;

2) conditions resulting from the system's interaction with the natural environment;

3) environmental conditions arising from the interaction of system elements and system equipment.

Types of these environments can cover a wide spectrum depending on the misssion, and the survival of equipment and crews requires a definition of these environments. Knowledge of environments that exist or are propagated in each mission state; i.e., prelaunch, launch, ascent, Earth orbit, etc. is necessary in designing protection or control elements. Examples of environmental conditions that may be encountered follow.

- Natural Environment
  - Planetary
    - Atmospheric
    - Thermal
    - Gaseous content
    - Gravity
    - Radiation belts
    - Magnetic fields
  - Space
    - Radiation
    - Meteoroids
    - Vacuum
- Induced Environment
    - Dynamic
    - Thermal
    - Radiation
    - Man
    - Vibration
    - Shock
    - Humidity
    - Thermal
    - Radiation
    - Meteoroid
    - Biological
    - Gravity

Several conditions establish the need for a central systems engineering environmental function. The environments involved in a system definition and its mission are derived by many disciplines in the development process. These environments become factors in the definition and design of system elements not directly involved in their determination. As with any parameters that affect many design activities, they must be controlled as system baseline requirements.

Another factor in achieving uniformity in system definition concerns the margin of safety for environmental stresses. Most environmental factors are described by statistical distributions. In the definition, design, and verification testing of the system, the model of the parameter is determined and then a design value is selected that includes a margin or safety factor. To achieve a uniform design confidence, the environmental group of systems engineering defines design values to be used in design of all system elements.

The system design problems are depicted in Figure 9.

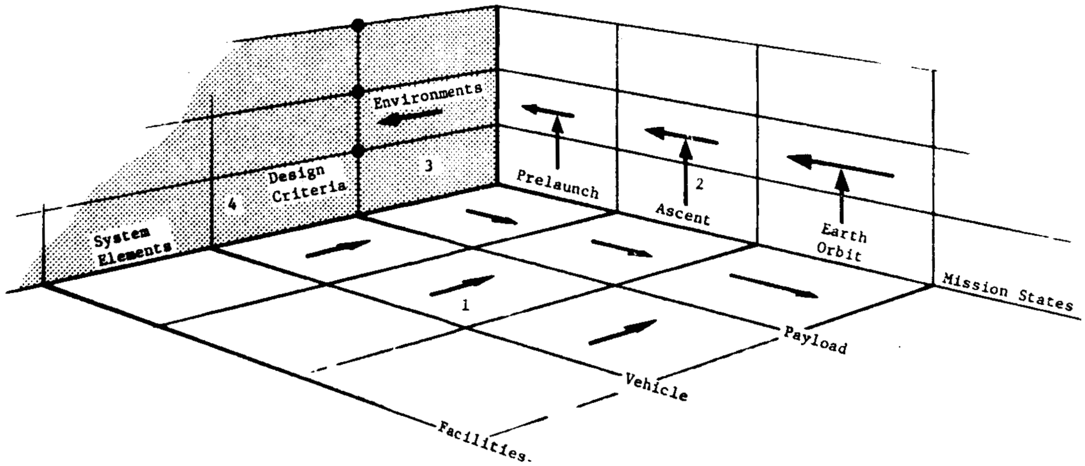



*Figure 9 Environmental Analysis*

In this figure, the interactions that comprise the systems environmental requirements activity are shown for a single system element. They include --

1) examination of the system element in each mission state;

2) identification and quantification of applicable environments for each state;

3) examination of the system elements interaction with these environments;

4) development of a design criteria to be used in definition/design of the system element.

In summary, the central systems engineering environmental group is responsible for environmental criteria tasks as follows:

1) Establish and maintain the program environmental design criteria, including thermal vibration, acoustics, shock, radiation, meteoroids, planetary environments, etc.

2) Act as the single focal point for environmental criteria control, specification, discussions, and presentations to customer.

3) When the program environmental criteria includes analyses from other functional disciplines, thoroughly review, understand, and approve the input analyses.

4) Assure that the rationale supporting each environmental definition is correct and thoroughly documented.

5) Verify environments with analyses and measurements as required.

6) Establish conservative margins between actual conditions and design and test conditions.

*Reliability* - In modern engineering technology, reliability may be characterized as a parameter of systems effectiveness concerning (1) probability of performance over a required period of time, (2) analysis of available strength against probable stress; (3) tradeoff of reliability against other desired qualities, (4) cost required to reach a given reliability goal, (5) achievement in production of the reliability inherent in the design, and (6) the optimum use of the product in service.

Reliability analysis has an influence on the performance of each of these items and applies mathematical models and statistical data to evaluate, compare, tradeoff, and optimize the effectiveness of a system.

Reliability engineering provides resources to address the problem of achieving acceptable dependability of the system in the performance of the intended mission. Reliability deals with the characteristics failure in system elements, and therefore treats a primary factor in mission success. The nature of total system reliability is complex, and the objective of reliability engineering is to provide an analytical basis for assessing the system reliability and to establish practical approaches to achieving acceptable results. The analytical methods provide a means of judging the general level of risk and inferring a probability of success. The practical measures selected are the means of achieving results that will be acceptable. The balance between these two activities provides means for a rational and planned influence on the system to achieve desired success probability. It should be noted that the problem of inferring a probable outcome in a complex system where limited data is available does not lend itself to precise allocations and summation of increments to yield total system assessments of reliability. The objective of reliability analysis is to establish that the margins of safety or protection are reasonable in the face of program and system limitations, and that a balanced solution to system reliability is achieved.

Reliability and reliability analysis play an important part in the system engineering process and in each of the system development phases. The reliability analysis provides a current assessment of risks involved, and identifies the optimum configuration and optimum operation to achieve the greatest effectiveness for the resources expended. In summary, the reliability tasks are as follows:

1) Establish reliability models.

2) Establish early identification of potential problems.

3) Establish reliability allocations.

4) Establish reliability specifications.

5) Identify and eliminate failure modes.

6) Determine design and operating margins.

7) Establish redundancy policy and criteria.

8) Participate in Parts, Materials, and Components Selection.

9) Prepare FMEA.

10) Establish procurement/supplier evaluation and control.

11) Verify launch operations - launch on-time criteria,
- hold criteria.

12) Identify critical parts.

13) Establish parts derating criteria.

14) Identify and participate in determining checkout frequency.

15) Identify critical storage time for applicable items (limited storage life).

16) Establish part selection criteria (high rel) (Mil Std) (comm).

17) Determine failure mode criteria.

18) Reliability provides a numerical evaluation of the risks and the system effectiveness probabilities.

19) Reliability identifies the optimum system and operation by evaluation of numerical trade studies on comparative designs.

20) Reliability identifies and eliminates or minimizes failure modes by the failure mode and effects analysis.

21) Reliability provides early identification of the problem areas.

4. <u>Crew/Mission Operations Discipline</u>

While many disciplines can be identified as systems engineering, the discipline associated with operations of manned systems crosses so many backgrounds that it can be included in systems engineering only after rather careful consideration of what the discipline can contribute and how it should be used. For reasons which go beyond the mere division of labor, it may be reasonable to support the view that the crew and mission operations could be beneficially held separate. Apart from these organizational tradeoffs, the role of crew/mission operations can be examined under the assumption that the discipline exists in a systems engineering organization without modifying the major conclusions.

One of the unifying elements that justifies crew and mission as a single discipline is the responsibility of determining how the human component in the system will operate and requirements and costs associated with this operation. The crew aspects of the disciplines are concerned with work loads, safety, optimum uses of man, and the design of the man/machine interface. The mission aspects are more concerned with sequences, schedules, information flow, and decisions. In respect to functions, crew specialists constantly review the assignment of a function to the crew in terms of the impact of the task on the crew. The mission specialists are more inclined to allocate mission planning, control, and evaluation functions to items, and are more concerned with system output than the impact on the men working the system. Naturally, these distinctions are both artificial and incomplete since both specialties require consideration for selection and training and must constantly work back and forth. If the discipline were perfect, throughout the development of a system the characteristics of the human component could be precisely stated in terms of what he (the human component) requires, what he can do, how his performance can be modified, how he interacts with other components, how he fails, and other engineering statements concerning component characteristics. Since the discipline is not perfect, statements about the component are very inexact, and testing and design acceptance of manned systems assumes a major program role.

In addition to engineering statements about the human component, the discipline contributes operations statements that concern system performance, workarounds, interactions with other systems, mission phasing, logistics, maintenance, and other domains not usually grouped with design. The discipline, then, is not restricted in interest to system design or manned flights. While it is a discipline that is difficult to bound, it seems to be restricted to the development of systems that use men to meet operational objectives. This distinction between system design and system development as an objective is often not clearly appreciated during the early phases of the development of a program, and initial allocation of functions may not give adequate weight to the role of the crew or the coordination between flight and ground operations.

Rather than describe the discipline in terms of its organization relationship or in terms of the technical backgrounds of the members of the discipline, it may be more efficient to address the problem of what the discipline contributes throughout program development.

*Crew/Mission Operations Inputs* - The use of boxes and lines to represent program events and system development sequences is misleading since they suggest start and end points when in fact there is overlap, rework, and successive iterations. The boxes should be used only as a rough map and calendar to keep track of the events that are associated with the inputs. (See Figure 10.)

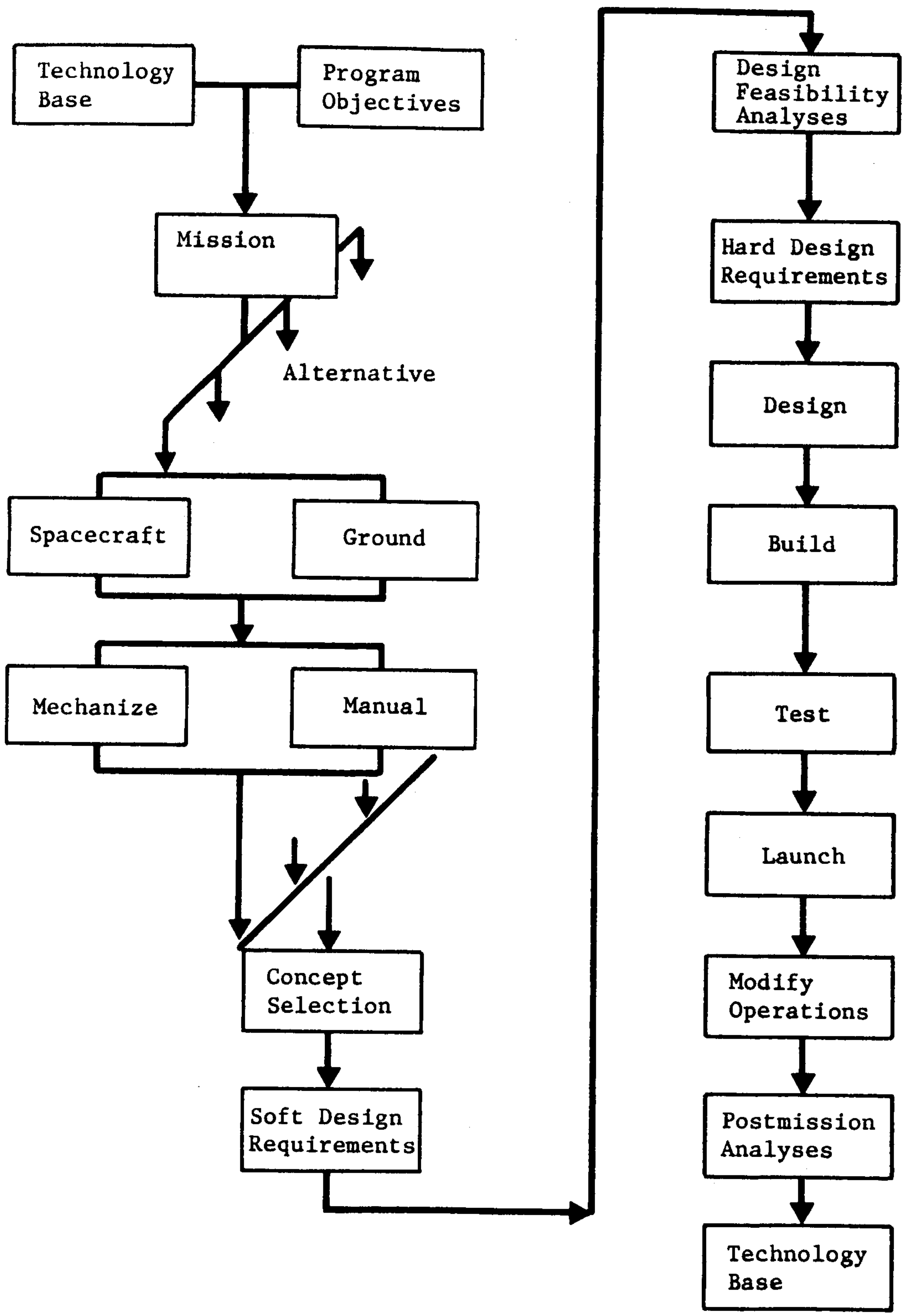



*Figure 10 Program Events and System Development Sequences*

During the formulation of initial concepts, crew/mission operations personnel are required to provide an accurate evaluation of the technology base. Key decisions about initial function allocations to the spacecraft or the ground and to men or machines cannot be made without a clear understanding of the technology base. Often the information includes availability of flight and ground personnel and the state of their training, so program dates as well as designs can be considered in the concept trade studies.

During the trade studies, crew/mission operations would provide representative duty cycles, mission sequences, safety analyses, training requirements, and other factors concerning the crew or the mission operation that would allow a comparison of one concept with another.

Following selection of a concept, preliminary "soft" requirements imposed on various systems will be tried to judge which requirements can be met and which should be made less severe on one system and more severe on another. Here again, balance between man and machine and between spacecraft and ground will be examined in more detail by a series of feasibility analyses until "hard" design requirements can be worked out. During the design phase, crew requirements and procedures will be prepared in the form of requirements documents and mockup, simulation, and trainer requirements describing time-phasing and fidelity. The degree of fidelity and the type of simulation or trainer selected will have great cost and time impacts. These requirements will be traded using crew confidence, procedures confidence, and mockup cost as the principal criteria.

During the design phase, use of mockups and preparation of analyses of crew tasks will produce changes to the design and the beginnings of operational procedures development. Using flight-similar articles (often referred to as trainers), operational procedures will be developed and the selected flight crew will begin practicing anticipated tasks. Designation of the ground team will begin and communications and responsibilities of the teams will be clarified. Design modifications will continue when operations required to meet mission objectives cannot be economically or safely performed with the designed hardware. These modifications can be used to provide valuable design feedback in preparation for the next mission design.

During the actual operation of the mission, the system engineering design team will be required to provide analyses of unusual or off-nominal performance of system elements and develop alternative methods of operation or inflight modification in support of operational personnel.

In summary, systems engineering functions associated with the crew/mission operations discipline are as follows:

1) Coordinate with all disciplines in optimization of mission objectives and requirements.

2) Generate data requirements necessary for mission operation and evaluation.

3) Generate mission documents such as various program support requests that are required by different technical disciplines.

4) Conduct mission analysis to determine: integrated timelining of events (i.e., crew, experiment, spacecraft, and system sequences); contingency planning; compatibility of systems versus mission requirements; identification of constraints associated with mission requirements; compliance with flight/mission program objectives; experiment and flight vehicle system data return requirements; airborne/ground net capability and compatibility required to satisfy data management requirements. These activities are performed in conjunction with trajectory analysis and navigation activities performed by other personnel.

5) Evaluate the technology base and provide initial allocation of functions to spacecraft versus ground and to manual versus mechanization.

6) Determine launch mission rules and launch constraints as imposed by flight operations.

7) Integrated flight mission rules.

8) Perform flight operations implementation of payload/experiment systems and consumables monitoring requirements.

9) Assist in training of flight controller and support personnel.

10) Determine operations support requirements.

11) Perform definition and implementation of simulations required for training and software development.

12) Perform ground network support analysis and requirements definition.

13) Determine technical operations support and/or flight controller responsibility during mission.

14) Determine flight controller and operations support procedures.

15) Determine flight operations and flight simulation ground equipment configuration requirements.

16) Integrate operations support software requirements.

17) Coordinate operations requirements generated by other engineering areas.

18) Determine antenna coverage requirements during abort and alternative missions.

19) Coordinate engineering discipline support required during operation of the mission.

20) Provide data concerning crew and mission operations for preliminary trade studies.

21) Perform crew operations activities as follows:

    a) Determine human factors design criteria, standards, and requirements.

    b) Perform crew task analyses, time lines and workload determination.

    c) Perform mission feasibility analyses and man/machine function allocations.

    d) Determine life support requirements and crew schedule constraints.

    e) Provide inputs to manned simulation plans, associated data analysis, and recommendations.

    f) Provide crew-oriented inputs to mockup and trainer requirements.

    g) Determine specific man/machine interfaces and verify system performance by test.

    h) Develop contingency procedures for crew.

    i) Assist in EVA equipment requirements and procedures development.

j) Determine crew station layout, control and display readability/ operability requirements and analyses; link analyses; anthropometric analyses; fault isolation procedures and critical skills analyses.

k) Provide design data during training, procedures development, operational and postoperational phases.

l) Assist in preparation of crew operating procedures and hand books.

m) Perform crew procedures integration and compatibility analysis.

n) Assist flight crews in system design reviews.

o) Review all GSE design for compliance with program human engineering requirements.

p) Determine crew recreation time requirements.

5. System Verification

Systems engineering verification provides skills and methods for planning and implementing an integrated design and premission verification program as a part of the definition/design of a system. As in other central systems engineering functions, design and premission verification requirements and approaches have an impact on all system elements and are a direct factor in mission success confidence. The objectives of this function are to establish consistent test checkout and analytical approaches for all elements of the system, and to realize the maximum confidence in mission success with minimum cost to the program.

System design and premission verification starts in the concept phase where general test and checkout philosophies are examined in conjunction with system operations analyses. In this phase of system development, concepts are identified and examined as part of operational availability feasibility analysis where reaction time or frequency of checkout are factors.

The main functional activities of system verification occur in the definition/design phase. In this phase, systems verification establishes the verification concepts and requirements baseline that governs the definition and design of mission and support system elements. The initial activity is the development of an integrated system verification plan. This plan is aimed at establishing consistent approach to testing and checkout verification in all design, development and premission states (development testing, qualification, production, acceptance, storage, system assembly, integrated system checkout, launch countdown) to assure that at each level of complexity, total system, system element, subsystem, component and part, that the verification approaches are consistent, complete, and provide a desired degree of confidence. Interaction with other design and systems engineering disciplines occurs in the systems analysis to find a compatible initial requirement that can be used to drive the definition process. Once these requirements have been set, they become part of the systems criteria and are directed to all disciplines. Subsequently, systems verification expands on these criteria as system element designs evolve and participate in trade studies where verification requirements are factors in the selection process. In the final stage of each phase, systems verification evaluates the system definition and design to determine that verification requirements have been completed and that the total system verification approach is complete. In summary, the following specific activities constitute the systems engineering verification functions.

Systems Test Integration and Requirements

1) Develop integrated test plans that define total program test requirements, including development, qualification acceptance, and operational testing.

2) Develop operational functional flows and timelines of program test and checkout requirements.

3) Define test support requirements necessary to accomplish test requirements at offsite locations.

4) Prepare and maintain the test section of system specifications and interface specifications.

5) Establish and implement test program trend data analysis.

6) Integrate detailed test requirements and success criteria for integrated system testing.

7) Define system retest requirements for component replacement policy.

8) Develop backout requirements for test phases where backout is critical to personnel or equipment.

9) Coordinate and document detailed engineering test requirements for special tests.

10) Review and approve test sequence plans and system level test procedures prepared in compliance with test requirements.

11) Monitor test program implementation to assure accomplishment in accordance with the intent of technical requirements.

12) Accomplish test analysis and prepare test reports on system level development and qualification tests.

Environmental Test Requirements - Responsible for environmental and qualification test requirements as follows:

1) Establish environmental test requirements for components, subsystem and system testing as required.

2) Coordinate and establish component test plans defining program technical requirements for component development, qualification and acceptance testing.

3) Review and approve environmental test fixtures and procedures including those required for qualification and environmental acceptance test (EAT).

4) Monitor environmental development, qualification, and EAT testing.

5) Review and approve qualification and system environmental test reports, and negotiate results with customer.

Systems Test Analysis and Control - Responsible for systems test implementation as follows:

1) Perform integrated mission/support equipment system analysis to implement system test sequencing and control for combined/integrated system test.

2) Define and control detailed step-by-step logic command/stimulus and/or expected response success criteria for item 1.

3) Review and approve all systems test procedures prepared to implement the tests of item 1.

4) Prepare and maintain documentation to identify usage and allocation of mission-peculiar hardware and software affecting acceptance test and operational usage of each article.

5) Provide engineering support required in above areas to implement rapid mission change, turnaround, and contingency operations.

6) Assure that instrumentation/data is provided to accomplish adequate system test performance evaluation and fault isolation.

7) Accomplish trend data analysis on system tests as required by the program.

## 6. System Design and Integration

System design provides and applies processes required to establish an optimized system technical approach (definition) from given requirements, develops compatible design requirements, and monitors the evolution of the design to assure that system design requirements are met.

The overall goal of systems design is to optimize the technical path from given system requirements through the verification phase of the program.

*System Definition* - The process of developing a system level design or design concept to meet the technical requirements is the system definition. This is accomplished through application and coordination of specialized engineering disciplines, past experience, and knowledge relative to the state-of-the-art, and culminates in the establishment of the gross configuration of the system elements. Although only basic approaches are defined at this point, considerable sublevel system design insight is required to reduce the risks of downstream iterations subsequently impacting the top level approach. This risk can be reduced by involving project management, key personnel from other systems engineering disciplines, and key design specialist personnel, as required, and by developing an accurate and thorough understanding of the given system requirements.

Systems engineering tools applicable to orderly establishment of a system definition include functional analysis, design synthesis, trade studies, and system block diagrams. For the resolution of critical, top level concept decisions, it may be necessary to employ tools of a more detailed nature; e.g., mathematical models or trajectory programs.

The approach resulting from this program phase will encompass both performance and top level design requirements and must be documented in a system block diagram, functional analysis results, or other formalized means, and preserved along with applicable trade studies to form a basis for the systems design criteria.

*System Requirements Definition* - Systems has the lead role in establishing, coordinating and documenting the system and subsystem design requirements, which will constrain and control the technical effort during the design definition phase.

This is accomplished through use of controlling systems and subsystems design criteria and interface control requirements. The process of establishing design criteria consists of technically interpreting the systems definition, defined above, in terms of, first, a systems design criteria, and subsequently, criteria for each significant subsystem or design discipline appropriate to the program. The process is a progressive analysis of functional requirements, leading to definition of a system of hardware, software, and technical tasks to fulfill the requirements, and generating the detail requirements for these elements. This process is continued to a level of detail beyond which technical assignments can be made to specialty technical groups with a low risk of experiencing system integration or compatibility problems.

The tools employed to develop these criteria include sizing studies, trajectory analysis, loads analyses, stability analyses, accuracy and tolerance analyses, etc. Systems engineering has primary responsibility for coordinating, generating portions of, and assuring compatibility of these criteria. All other systems engineering disciplines are intimately involved in this task, and the technical design areas have significant contributions, particularly in the generation of subsystem criteria.

Products of the system design requirements function follow.

*System Schematic Diagrams* - First level schematics depict system segments and end items and the interface relationships among them. Second level schematics are expansions of the first level schematics and are prepared for each subsystem or end item to depict the subsystem and major component interrelationships. These schematics may be incorporated into the system and subsystem design criteria, respectively.

*Functional Time Line* - This depicts in sequential format the time/event relationship constraints for the system mission or operation. This may also be incorporated into the design criteria.

*Design Criteria* - The system criteria establishes requirements and constraints that will be imposed upon the design of the total system. This criteria contains the performance, operation, and design implementation requirements for the major system elements. This criteria expands the customer requirements contained in the SOW and specifications, and is based on *System Definition*, Section b, 5 of this chapter.

Subsystem/element/end item criteria contain the performance, operation, and design implementation requirements for the system segments, subsystems, and end items of hardware and software. These criteria expand the requirements contained in the systems criteria so that a competent designer or design organization can design the element, subsystem, or end item without further definition of requirements.

*Interface Requirements* - Interface requirements define design and functional interrelationships among the major system segments, or between segments that are independently developed; e.g., subcontracted end item, or associate contractor program. These requirements may be documented in separate interface control documents, or may be incorporated into the system and subsystem design criteria.

Requirements that are contained in the various criteria documents listed above must be based upon sound rationale and should be traceable to their origin. The requirements in these documents should reflect results of functional analyses, allocation of system requirements, trade studies, sizing analyses, customer direction, etc. Systems design personnel are responsible for documentation and dissemination of system design requirements, and for maintaining requirements until (typically) the critical design review point in the program.

*System Requirements Integration* - Systems design assures that system design requirements (described above in *System Requirements Definition* are, in fact, complied with as the design development phase of the program progresses.

The system design goal of this task is to assure that the design develops as a system rather than as a collection of unrelated items. This is accomplished by a continuous, systematic surveillance of design development outputs, including end item specifications, interface specifications, analytical studies, detail design drawings, functional schematics, test data and reports, and acceptance test specifications and data. These outputs are reviewed for compatibility with the intent of requirements documentation. Systems design is responsible for conducting compatibility reviews, identifying and tracking the problems, and coordination of systems-related corrective action.

Systems design will direct particular attention to surveillance of interfaces between adjacent designs created in separate areas of responsibilities to assure that the designs are mutually compatible.

Although requirements integration is a continuing process throughout the design development phase, program reviews (described in the following paragraphs) offer discrete checkpoints in the program where formal integration assessments can be made.

*Design Reviews* - Design reviews are formal, technical reviews of a system or system segments to establish adequacy and system compatibility of design. The purposes of the reviews are to assure program management, central engineering, and/or customer program monitors that the studies performed and the products designed are of the highest possible quality consistent with time and budget limitations, and to assure that these products satisfy system design requirements.

Design reviews may be scheduled at various stages in a program, depending on particular program requirements, but generally reviews are held to confirm establishment of design concept, after preliminary design is complete, and prior to release of final engineering.

Systems design personnel, in conjunction with project management, schedule convene, and conduct the design reviews. Responsibility for specialized disciplines presented at design reviews is delegated to key personnel from other systems engineering organizations (e.g., Reliability) and from the specialist design groups (e.g., Structures). It is also the responsibility of systems design personnel to assure the presence of appropriate personnel from without the immediate project area so that a broader base of technical competence and the experience gained on other programs may be applied.

The presentation approach used in design review is aimed at verifying traceability of evolving design factors and compatibility with the documented design requirements. Methods employed may be a complete, systematic, checklist presentation of design requirements versus design status; or a more efficient presentation "by exception" wherein only those areas are presented that are known or suspected problems.

In summary, within this discipline, system criteria, technical specifications, and other system engineering documentation are developed and maintained. Overall system design is established and all elements are integrated into the functional system. The major specific tasks to be performed follow.

1) Establish system requirements and define basic system configurations.

2) Perform systematic system and subsystem design analyses from compatibility and functional aspects.

3) Conduct system design reviews.

4) Perform technical reviews and assessment of all design change activity.

5) Participate in or lead trade studies for system design optimization.

6) System Element Integration --

   a) Perform overall integration between major system elements.

   b) Define interface requirements and constraints between major system elements.

   c) Coordinate interface definition activity within engineering functional activities.

   d) Serve as single point engineering contact for systems integration among organizational elements.

   e) Conduct design and integrity reviews and compatibility analysis.

7) Electromagnetic Compatibility --

   a) Generate and maintain EMC control and test plans.

   b) Participate in or chair EMC technical working groups.

   c) Review all design engineering for compliance with requirements.

   d) Monitor subsystem EMC tests and conduct system EMC demonstration tests.

   e) Establish design requirements for EMC test tooling.

8) Design Review Management --

a) Establish need for reviews, types of reviews, review schedules, and major participants, through coordination with project.

b) Establish review teams.

c) Prepare design review directives.

d) Participate in management panel as secretary, recording action items, and assuring their inclusion on proper open items list.

e) Maintain records of reviews, track action item closures, and method and suitability of disposition.

7. Integrated Logistics Support

The logistics support functional activities are included under central systems even though it is generally a separate organization. The reason for this is that the integrated logistics support elements make up a complete system in the sense that they consist of equipments, facilities, personnel, and procedures that function together to determine mission related requirements. These requirements are correlated with the mission system and the accomplishment of the overall mission objectives. This relationship is illustrated in Figure 11.

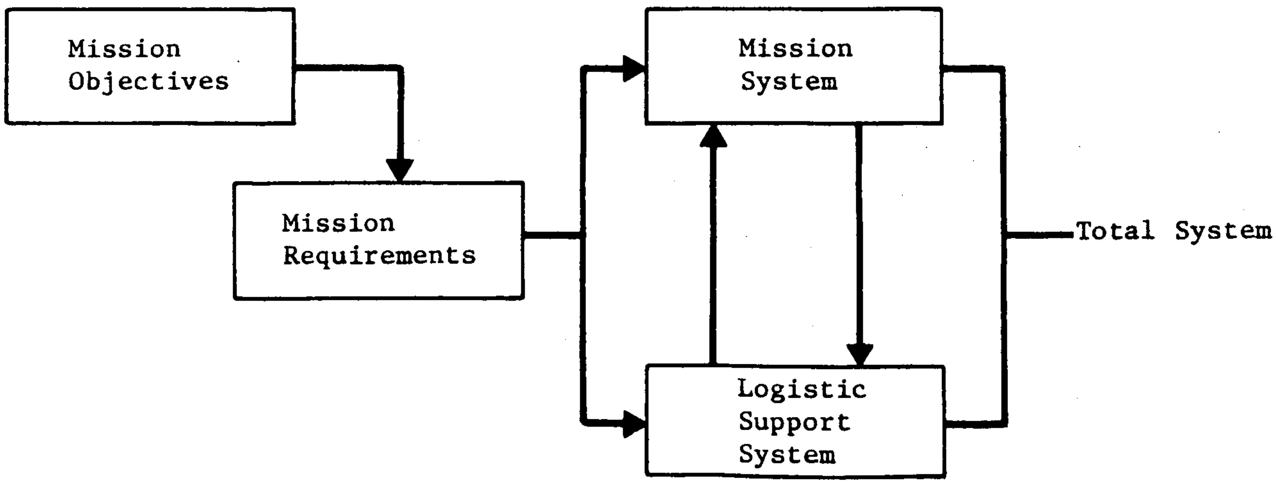



*Figure 11 Total System Configuration*

The systems engineering functional activities relate directly to the effectiveness of the system in performing the mission and in minimizing the cost, and in cost effectiveness. The logistics support is one of the primary factors in achieving a specified level of availability. This parameter is a measure of assurance that the system will be ready to perform the mission when called on to do so.

To provide effective logistics support for a system, with maximum cost effectiveness, an optimum balance must be maintained between the quantities and types of spares selected, and the maintenance requirements, reliability, and maintainability implications. Provision of the least costly set of spares may create a repair/replacement situation that is very costly, or conversely, the most economical maintenance situation in terms of equipment and personnel may require a costly set of spares to complement it. Added to the complexities of achieving this economical balance of spares and maintenance requirements are such specific requirements as maintenance reaction times, maximum allowable downtime, and maintenance of acceptable levels of system safety.

To achieve optimum system effectiveness, analyses to define logistics requirements must begin early in the system concept and definition phase and continue as an iterative process through completion of detail design. The logistics analyses must also be integrated with other systems analysis/systems engineering activities because of interactions with other elements. The many conditions imposed create a requirement for objective, systematic methods for evaluating alternatives; i.e., tradeoff techniques to assist the decision making processes. The general approach to this problem is to express all maintenance effort (manpower, test equipment, technical data, and maintenance support facilities) using personnel of average skill under operational environment conditions in which scheduled and unscheduled maintenance will be performed. Note that this characteristic should be distinguished from "repairability" with which it is often identified as synonymous, and which excludes the additional coverage of ease of preventive maintenance and servicing.

Maintainability influences the downtime, once a failure has occurred. Downtime can be decreased by a system that can be readily repaired or serviced.

Logistics depend upon those characteristics of design and installation that determine the probability that the system will conform to specified operational performance requirements, or state or readiness, when supported within the resources of the available personnel subsystem and logistics support and maintenance. It is an element of both logistical systems effectiveness and operational readiness and, thereby, of operational systems effectiveness. Logistics supportability can be evaluated as the economy in time, men, support materiel, and facilities, and their cost.

Logistics influence availability through waiting time for repair or service which, in turn, may be functions of spares, distance, speed, and design delays. It also includes waiting for parts, facilities, personnel, etc to become available.

At the system level, modeling techniques are developed for combining maintainability, safety, reliability, etc parameters to establish values of these parameters that meet the availability requirement for the system. Probability of launch-on-time analysis models, for example, provide the means for examining the problem in terms of mean times between failure (MTBF) and mean time to repair (MTTR), and the launch operation time line. Logistics together with system effectiveness develop the means for translating MTBFs, MTTRs, failures critical to safety, FMECAA, into meaningful design parameters.

This translation takes the form of reliability, maintainability, and logistics criteria and policies that govern the definition/design of the system.

The logistics criteria ultimately selected for the definition/design of the system must meet the following requirements. They must be --

1) quantitative;

2) sufficiently meaningful to the system designer and system analyst to permit their use as design and evaluation criteria for a given system;

3) sufficiently meaningful to the user and mission analyst to permit their value to be specified and interpreted in terms of the mission.

The systems engineering activities involved in the development of the logistics support system follow.

1) Develop logistics baselines that delineate all the tests, checkout, and operational functions for which logistics support must be provided.

2) Determine a maintenance policy for the total system; i.e., where maintenance will occur (depot or field), level of maintenance (black box or component), testing requirements after repair, preventative maintenance versus corrective maintenance, etc.

3) Determine spares policy for all operational phases of the mission system; i.e., level of spares, location of spares, spares determination, spares provisioning, etc.

4) Determine equipment requirements for maintenance activities; i.e., tools, tool kits, test equipment, ground support equipment, etc.

5) Determine facilities requirements.

6) Determine personnel and skill requirements.

7) Determine procedure requirements.

8) Determine base support requirements for maintenance activities.

9) Determine training requirements, training equipment requirements.

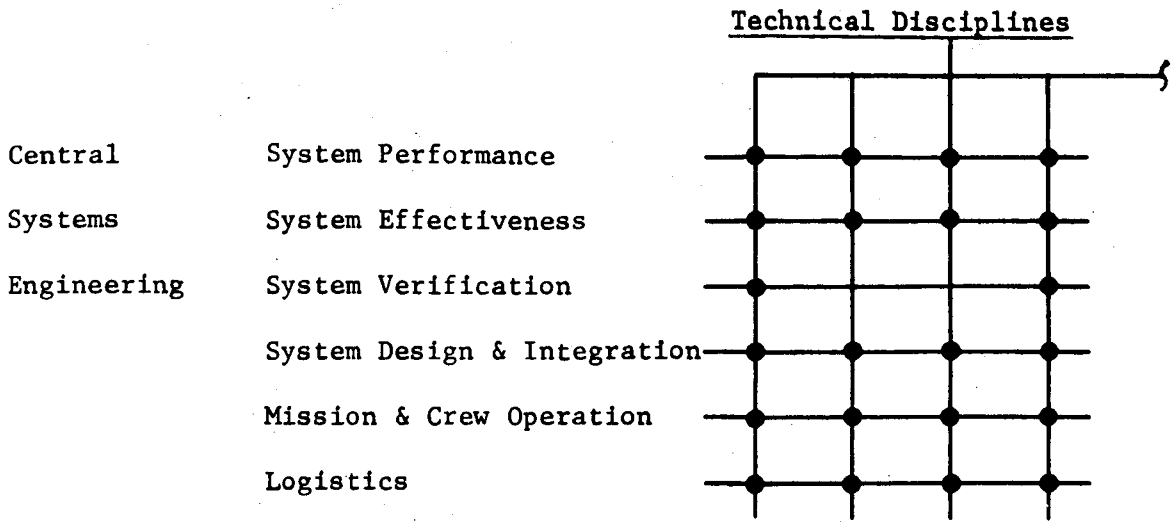
10) Conduct training courses.

11) Plan transportation activities.

## 8. Summary

The central systems engineering discipline provides skills and procedures to address the system development problem in terms of the factors that make up the design verification and use of the system. These factors cover the specialist areas of design and integration, system performance, system effectiveness verification and crew/mission operations. These factors all have the characteristic of broadly affecting all elements of the system, and thus affect "what technical disciplines do" in the definition of concepts and design requirements for system elements. This relationship results in the matrix organization structure shown.

The crossover points identify interrelationships in which technical disciplines participate in the definition of the system. The nature of the relationship and the functions performed by the technical disciplines in the total system definition are discussed in the next section.


Technical Disciplines
Central
Systems
Engineering
System Performance
System Effectiveness
System Verification
System Design & Integration
Mission & Crew Operation
Logistics

## B. SYSTEMS ENGINEERING FUNCTIONS OF TECHNICAL DISCIPLINES

Design disciplines are an integral part of systems engineering and perform functional activities that have a direct bearing on the consistency and completeness of the total system. The system functional activities of design disciplines include management activities performed at the organization level and thos performed by the design discipline groups involved in system development. In the following section, management activities of design disciplines and the subsequent system functional activities of the technical discipline groups will be covered.

### a. System Functional Activities of Technical Discipline Organizations

The technical disciplines engaged in a system development are organized in many ways, depending on management judgment. Whatever the structure, specialists are grouped together from both a project and a disciplinary point of view. Figure 12 illustrates this concept. This section is concerned with systems engineering activities of these organizations, the objectives, and their relationship to the central systems discipline.

These systems engineering activities may or may not be identified as organization elements but the roles and responsibilities nevertheless must be identified and recognized as part of each design discipline. Implementation of systems engineering as a workable factor in the engineering organization, the relationship between the systems engineering discipline and those of the technical disciplines must be specific and well defined.

The functional activities of the engineering organizations (electrical/ electronics, structure/mechanical, flight mechanics/aeroballistics, etc), are uniformly the same and represent the means for implementing systems engineering activities. These activities fall into the categories of requirements synthesis and design, and evaluation.

#### 1. Requirements Definition and Control

In the definition and design phases, system requirements are compiled and issued as direction at the beginning of each phase. During the phase activity these baseline requirements are maintained (modified and expanded), and at the end of the phase are source data for specifications that govern the next phase activity. The systems function in each design organization performs the following activities for the specialist groups represented.

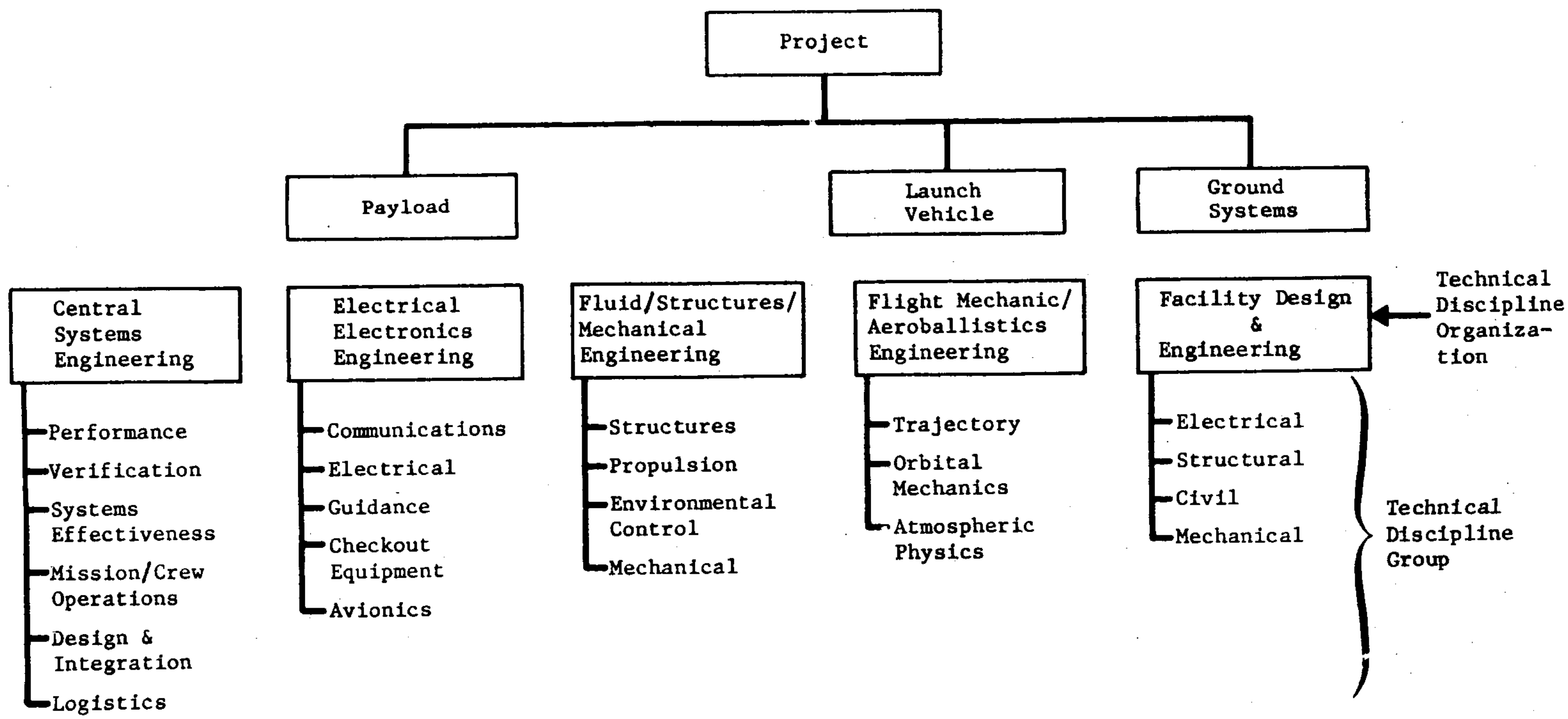



*Figure 12 System Functional Activities of Technical Discipline Organization*

1) Participate in the initial requirements analysis for expansion of requirements into a baseline; for example:

   Flight mechanics/aeroballistics --

      Identify and describe reference trajectory.

      Define reference atmospheric model.

   Structures/Mechanical --

      Identify approved materials list (flammability/outgassing).

      Define system outboard/inboard system profile to be studied and/or defined.

      Identify dynamics characteristics.

   Electrical/Electronics --

      Identify basic electrical power type and quality.

      Identify initial allocations to all users.

2) Provide the means for implementing system requirements in each design specialty area and assure that each design specialty area identifies and employs these requirements in the definition/design process.

3) Maintain cognizance of all deviations from system requirements and coordinate these with central systems and obtain disposition (approval/disapproval).

4) Maintain visibility to the expansion of requirements in each specialty area (guidance, structure, electrical power, etc) by maintaining functional models, block diagrams, schematics, and other descriptive data.

5) During definition/design, compile and integrate requirements that must be implemented by other organizations, and coordinate with the receiving organization; for example, all electrical/electronic systems facility requirements would be compiled and described and transmitted to the organization responsible for further compilation and integration prior to transmission to the facility design agency. This activity would be performed using the documentation and procedures specified by central systems.

6) Assure that the methods and documentation for identification, functional definition and solution of interfaces is employed.

7) Participate in interface panels and assure that proper specialists are involved.

8) Maintain cognizance over scheduled commitments and identify technical requirements inputs required as well as outputs to other organizational elements.

9) At the end of each phase, assure that the output specification approaches defined by central systems are implemented.

10) Compile specification requirements and provide them to central systems for integration into specifications that will govern the next phase activity.

11) Provide task data definition for inclusion in the SOW, WBS, and data requirements lists for RFP and contracts for the next program phase.

12) Identify general requirements for methods/techniques and design, and construction standards that govern the next phase activities.

## 2. Synthesis and Decisions

Within each design organization the definition/design activities subsequent to definition of requirements is the selection of a design solution that best meets the composite requirements. In this activity, the systems engineering element of each design organization provides the skills and resources to assure that the selection of solutions is based on merit to the system, and that the solutions (configuration, preliminary, or detail design) are integrated into the system. The specific functional activities follow.

1) Assure that the methodology for conduct of trade studies is implemented by design specialist.

2) Provide an identification of all trade studies that have been identified as potentially having impact on the total system.

3) For the trade studies in item 2), review and evaluate the trade studies for compliance with requirement for content and selection criteria.

4) Act as a focal point contact with central systems and the project for trade studies involving other organizations and design disciplines.

5) Maintain a list of problems, open items, discrepancies, and follow up on their resolution.

6) Provide a single point contact for interface with central systems specialists (reliability, safety, verification, etc) for the implementation of these requirements into the synthesis solutions.

7) Maintain control over simulations and performance models that form the basis for sizing and allocation of system performance; i.e., trajectory simulation, structural model, analysis model, guidance error analysis.

8) Maintain cognizance of configuration and design solution description and backup data (schematics, drawings, analyses, studies, etc).

## 3. Evaluation

The evaluation of results in the definition/design phase is made up of periodic indepth assessments of the development results. These assessments are made at all levels of system complexity and program organization to determine that the planned cost, schedule, and technical results are being achieved. The types of reviews in a program are program status, program baseline, system design, detail design, change control board meetings, and intercontractor or agency reviews.

In each of these activities, the systems engineering group of the technical organizations involved will --

1) Provide representation for the technical speciality groups involved in program and system reviews.

2) Present technical status and report on problems.

3) Plan and conduct design reviews of each subsystem and follow up on problems and discrepancies.

4) Review and assess program and system changes to concepts, requirements, and design solutions for impact on subsystems.

In summary, the systems engineering element of each design engineering organization performs functions that implement the central systems requirements and provide the focal point for technical specialties in interaction that takes place between central systems and project functions.

b. <u>Systems Engineering Functions of Technical Discipline Groups</u>

The engineering and scientific disciplines provide skilled resources that transform mission requirements into solutions described by performance and design requirements and system element concepts. These disciplines are identified and assembled by project management in each program phase and make up the technical development team. These disciplines provide the creative and innovative skills to conceive and define equipments facilities, personnel, and procedures that work together and collectively constitute the total system.

The functional activities of these technical disciplines can be of two types: those that have a significant bearing on the total system, and those that have impact on the characteristics and performance of a subsystem resulting in no significant system effect.

The systems engineering functional activities of technical disciplines are those that directly involve selection of a solution that best meets the performance requirements of the mission and system design requirements.

The mission performance requirements are those that can be traced directly to mission requirements of each mission state; i.e., delivering the payload, performing the object mission, and returning the payload and/or data. To illustrate this type of mission requirement, the mission analysis of a payload delivery system identifies a guidance and navigation accuracy requirement. Guidance and navigation design specialists would conceive flight and ground guidance schemes to achieve this mission capability. In this example, the guidance discipline would thus directly impact a primary mission requirement.

The system design requirements are those that central systems engineering and other technical disciplines establish as a part of the system definition/design process that must be implemented by a technical discipline for the system to be complete and integrated. To illustrate this, the best system solution to the guidance and navigation problem, the guidance discipline is faced with the following requirements:

mission accuracy;

reliability allocation;

weight allocation;

mission duration;

safety requirements;

maintainability requirements;

crew control requirements;

attitude control requirements;

electrical power allocation;

flight controls performance characteristics;

propulsion characteristics;

mission sequencing requirements.

These and other interrelationships define the type of problem faced by each design discipline in conceiving, defining, and describing a design solution.

The interrelationship with other disciplines and within the central systems engineering discipline is illustrated in Figure 13. This figure shows that each discipline is a focal point for a specific part of the system and has an iterative relationship with these disciplines.

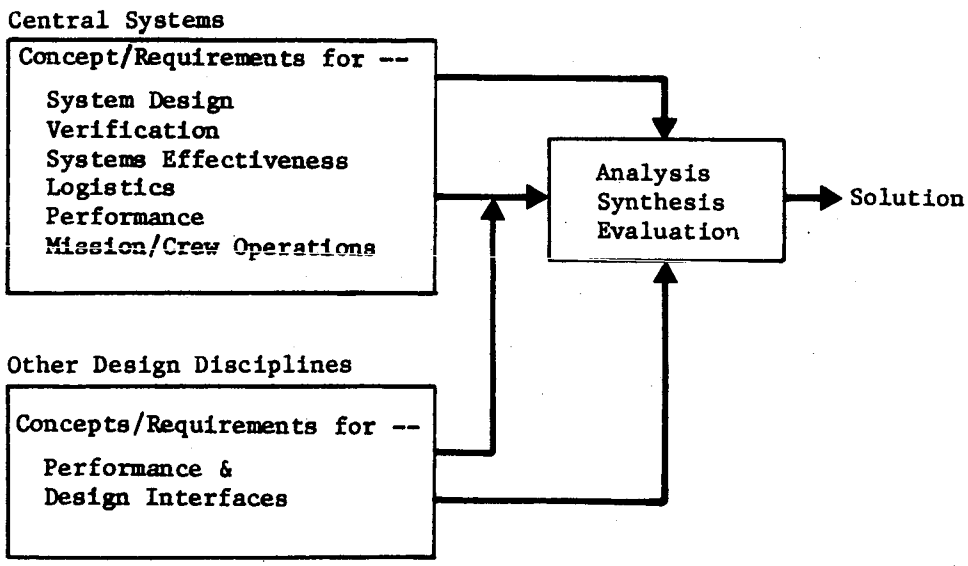



*Figure 13 Central Systems Engineering Discipline Interrelationship with Other Disciplines*

The synthesis of solutions by technical disciplines of system elements is an integrated team activity in most cases. The performance and design characteristics of system elements are highly correlated and it is not generally possible for a solution to be developed independently of other disciplinary activities. The definition of guidance equipment by a guidance discipline is an example of this. The system performance sizing is a highly correlated interaction of guidance, propulsion, structure, flight controls and flight mechanics disciplines. These disciplines come together to describe the mission problem in terms of integrated analyses and simulation studies with the objective of finding solutions that are mutually compatible and meet the overall system performance.

Another type of systems engineering functional activity involves setting requirements or defining solutions that have a broad effect on other elements of the system. Each discipline, devoted to definition of some portion of the system makes decisions that must be considered in other system element designs. For example, the following are established by design disciplines that have a broad system effect:

1) *Approved Material* - Materials specialists determine the materials properties that are necessary from the standpoint of mission compatibility. The result is an approved list of materials that must be used in all designs. The materials and processes characteristic may be, as in the case of a manned system, flammability and outgassing.

2) *Electrical Power* - The electrical engineering discipline determines the type of electrical power to be generated and distributed to the system equipments. This definition of voltage, frequency, and allocated capacity and grounding philosophy become system requirements that affect the definition and design of other system elements and subsystems.

3) *Communications Capacity* - In sizing the communication system, communication specialists determine the capacity (number of channels, number of functions, etc), and allocate these to users. The allocation of capacity together with sensitivity and accuracy of this system become constraints that affect the subsequent design of other system equipments.

This type of "system" requirements become, part of systems requirement baseline developed and issued as a directive by central systems engineering for each system development phase.

The design disciplines also perform systems engineering activities as a part of the management and execution of the development in each phase. As described in Section V,A,a, central systems engineering functional activities, a key factor in achieving total system objectives is a baseline requirements management approach. In this approach integrated and compatible requirements initiate each phase and are maintained and updated during each phase by central systems engineering. Progressively, baseline requirements are updated by formal program and design reviews.

The design disciplines are involved in this activity in terms of --

1) contributing to the initial requirements;

2) participating in the maintenance (revision and update) of system requirements;

3) providing output results of phase activity (configuration, description, and performance and design requirements);

4) supporting and participating in program and design reviews;

5) participating in resolution of interfaces between system elements and subsystem.

Another type of technical discipline systems engineering functional activity, an integration activity, results from the organizational structure of the program. Where the system elements are developed by a combination of contractors and agencies, the definition of technical requirements established the need for a special integration activity. An example of this is found in thermal analysis. The thermal control requirement for a spacecraft system is a function of an integrated thermal analysis of the spacecraft in each mission state. This spacecraft may be composed of a number of modules and a variety of payload and engineering equipments which involve several contractors and agencies. The analysis that sizes and defines requirements for each module must be an integrated model of the total spacecraft definition would therefore develop, in conjunction with the module contractors and agencies, an integrated thermal analysis model which would be used to size the thermal control system. The technical discipline charged with thermal analysis in the spacecraft program organization would perform this function. This type of design discipline integration activity has a significant impact on the consistency and completeness of the total system. Such activities are a part of the interface definition and form the basis for making interface decisions and verifying the validity of interface solutions.

In summary, the technical disciplines in the system program organization perform systems engineering functions to integrate the activities within the discipline to assure that the requirements definition performed by elements of the system are consistent and constitute a total system solution. In general, these functional activities follow.

1) Integrate requirements.

2) Identify and select concept candidate.

3) Establish and allocate subsystem requirements.

4) Perform integration analyses for requirements definition and system concept definition.

5) Perform interface definition and coordination.

In general the systems engineering functional activities of the technical disciplines are described as follows:

1) Perform an analysis of mission, systems and subsystem requirements and identify the concepts that are candidate solutions.

2) Implement the system trade study requirements provided by central systems in selecting feasible approaches.

3) Develop models, simulations for allocating, sizing, and evaluating performance and design requirements and solutions for subsystems of system elements.

4) Generate and provide to systems engineering performance and design requirements and constraints that broadly affect the total system.

5) Collect requirements that affect other system elements and provide them to the organizational elements that are charged with its design.

6) Assure that interfaces between subsystems are completely defined in terms of requirements and solutions.

7) Participate in interface working groups for the resolution of interface definition and solution.

8) Plan, organize, conduct, and follow up on design reviews of subsystems periodically in the development process to assure system requirements are being adequately implemented.

9) Support system and program reviews with data and representatives to assist in the examination of the system elements for system compatibility.

10) Develop and maintain descriptive data showing subsystem functional, performance, and design characteristics, and serve as a single point contact with project and central systems engineering.

11) Compile and provide to central systems engineering output results of each program phase for inclusion in specifications that will govern the next phase activity.

12) Provide task definitions, data requirements for inclusion in WBS, Statements of Work and data requirements lists.

13) Provide applicable design and construction and methodology standards that should govern the next program phase.

The specific systems functional activities of individual design disciplines are in many cases unique to the system element or subsystem being defined. Since there is a wide variety of design disciplines, the system engineering activities of a representative set of disciplines are discussed in the following paragraphs.

Figure 14 represents the fundamental design process showing the functions of central systems engineering and the technical disciplines. The upper part of the matrix shows the requirements definition and synthesis involved in a typical launch vehicle system development, while the lower part of the matrix shows the evaluation process of the system element concepts as performed by central systems engineering.

In Figure 14 typical system elements are shown on the left side of the matrix; at the top typical technical disciplines that are involved in the design of the system elements, and the system requirements that are imposed on the elements are shown. Shown in the vertical axis of the matrix is the source of requirements for the design of the system elements (the upper part of the matrix) and the resultant design concept (the lower part of the matrix). The source of requirements is indicated by a solid dot (●) under each technical discipline or system requirement that

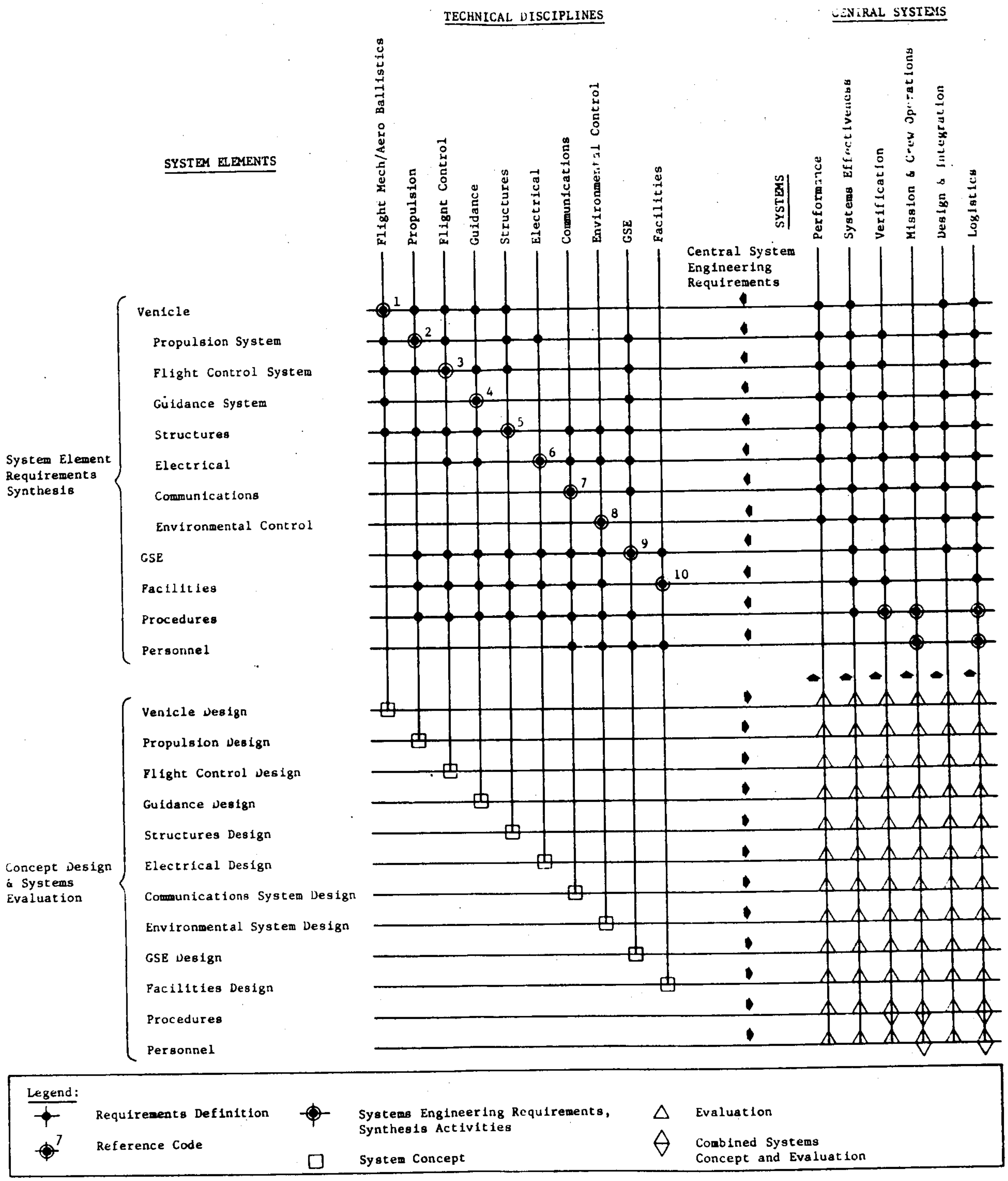



*Figure 14 Technical Discipline Engineering Activity Matrix*

impacts the element design concept. The resultant design concept is indicated by □. For example, the propulsion technical discipline has prime responsibility for designing the propulsion subsystem; the design of the propulsion subsystem, however, impacts and imposes requirements upon the design of the flight vehicle, the flight control subsystem, and the structures subsystem. It is possible that each of the technical disciplines can impact and impose requirements upon a given system element. It is for this reason that all the requirements from each of the technical disciplines, as well as the systems requirements, must be considered in a system element design.

The horizontal axis of the upper part of the matrix shows the possible requirements that must be considered in the system element design, and the technical discipline that has the responsibility for synthesizing the requirements for the system element design. For example, the flight control subsystem must consider requirements from the technical disciplines of flight mechanics/aeroballistics, propulsion, flight control, guidance, structures, and GSE as well as the system requirements of performance, system effectiveness, verification, design and integration, and logistics. The synthesis of all these requirements is a systems engineering activity performed by the technical discipline having responsibility; in the case of flight controls, the flight controls technical discipline. This responsibility is noted on the matrix by the symbol ◉. These requirements must be approved by central systems engineering prior to concept definition/design.

In the lower part of the matrix, the system element designs are shown on the left side. The requirement against which the system element design must be evaluated is indicated by the symbol △. For example, the communications subsystem must be evaluated in terms of its performance capability, systems effectiveness, verification requirements, design and integration requirements, mission and crew operations requirements, and logistics requirements.

The above described process is highly iterative and must be continually updated as design progresses.

## 2. Examples of Systems Engineering Functions

*Flight Mechanics/Aeroballistics (Figure 14 Item 1)* - The development of an aerospace system in general involves payload and delivery system elements and the definition and design of each is separate but highly correlated. Figure 15 shows, in block diagram form, the life cycle sequence for a launch vehicle definition and design. The payload performance and design requirements lead the

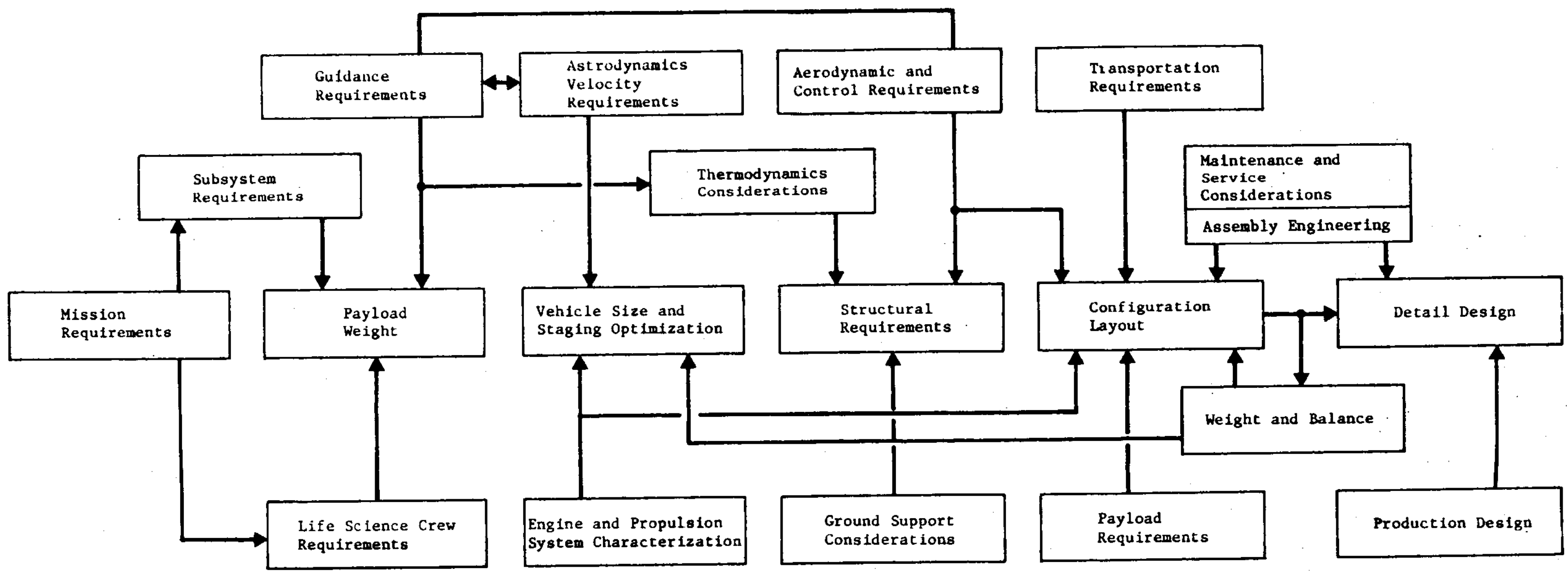



*Figure 15 Life Cycle Sequence*

vehicle activities and, in this discussion, these are assumed as initial conditions that drive the sizing of the booster.

The matrix in Figure 14 shows the discipline involved in the performance and configuration synthesis of the vehicle. These are flight mechanics/aeroballistics, propulsion, guidance, flight controls, structures, and central systems engineering.

These disciplines constitute a systems engineering team whose primary objective is to select a concept and size the performance of subsystems to achieve the best solution to the mission/payload requirements.

Flight mechanics/aeroballistics is the focal point or lead discipline. This discipline performs the initial analysis of the mission to establish the performance requirements that must be satisfied by the system, and as such performs a systems engineering function. These activities result in determination of the --

1) flight path (trajectory);

2) system accuracy requirement;

3) energy requirement ($\Delta v$);

4) natural and induced environment.

This mission problem analysis centers on a simulation of the mission that permits examination of performance parameters and system design characters. After initial mission requirements have been established, the next step is to examine the subsystem concepts and select, on the basis of performance capability, the configuration that meets the mission requirements. Where several concepts are being composed, performance data is developed in parametric form to permit selection of the candidate subsystem, (propulsion, for example) having the most benefit in terms of $I_{sp}$, weight, state-of-the-art considerations, and cost. The initial sizing of the vehicle results in parameters that provide the basis for subsystem definition.

These parameters include --

1) specific impulse of engines selected tentatively for the individual stages;

2) velocity requirement for the mission under consideration;

3) propellant fraction of individual stages estimated, based on the selected state-of-the-art, design features, and the thrust-to-weight ratio selected;

4) payload ratios desired as target values, based on the theory of stage optimization;

5) takeoff thrust, tentatively selected for the vehicle under consideration;

6) takeoff acceleration selected with consideration of performance and launch dynamics.

As shown in Figure 16, the objectives of the next phase of performance analysis is to develop preliminary weight breakdown, net payload capability, and vehicle performance parameters.

The stage specific impulses and the velocity requirement result in an overall effective mass ratio. Propellant fraction and payload ratio result in an average structural factor. This and the total mass ratio result in the optimum number of stages required, and give a first estimate of the growth factor (takeoff weight/payload weight). Combining this with the takeoff acceleration, gives a first estimate of the total weight-carrying capability (weight of instrumentation, guidance and control components, payload container, and net payload), defined as the dry gross payload.

A preliminary optimization of the propellant loadings of the stages which in turn allows more detailed weight estimates of the subsystems and components follows.

The flight mechanics/aeroballistic discipline performs the lead system function in initial sizing, which is one aspect of the system operational analysis of the definition/design phase. The subsequent verification of definition phase results involves an expansion of the simulation model to take into consideration structural characteristics (loads). When this verification of primary performance has been made, preliminary design of vehicle subsystems can be performed.

In summary, the flight mechanics discipline functions as the lead in the performance sizing and optimization of the vehicle system. In this capacity the requirements for propulsion, guidance, flight control structure, and mass properties of vehicle and payload are brought together and resolved into a compatible set of requirements that meets the mission requirements. This discipline performs the following systems engineering functional activities:

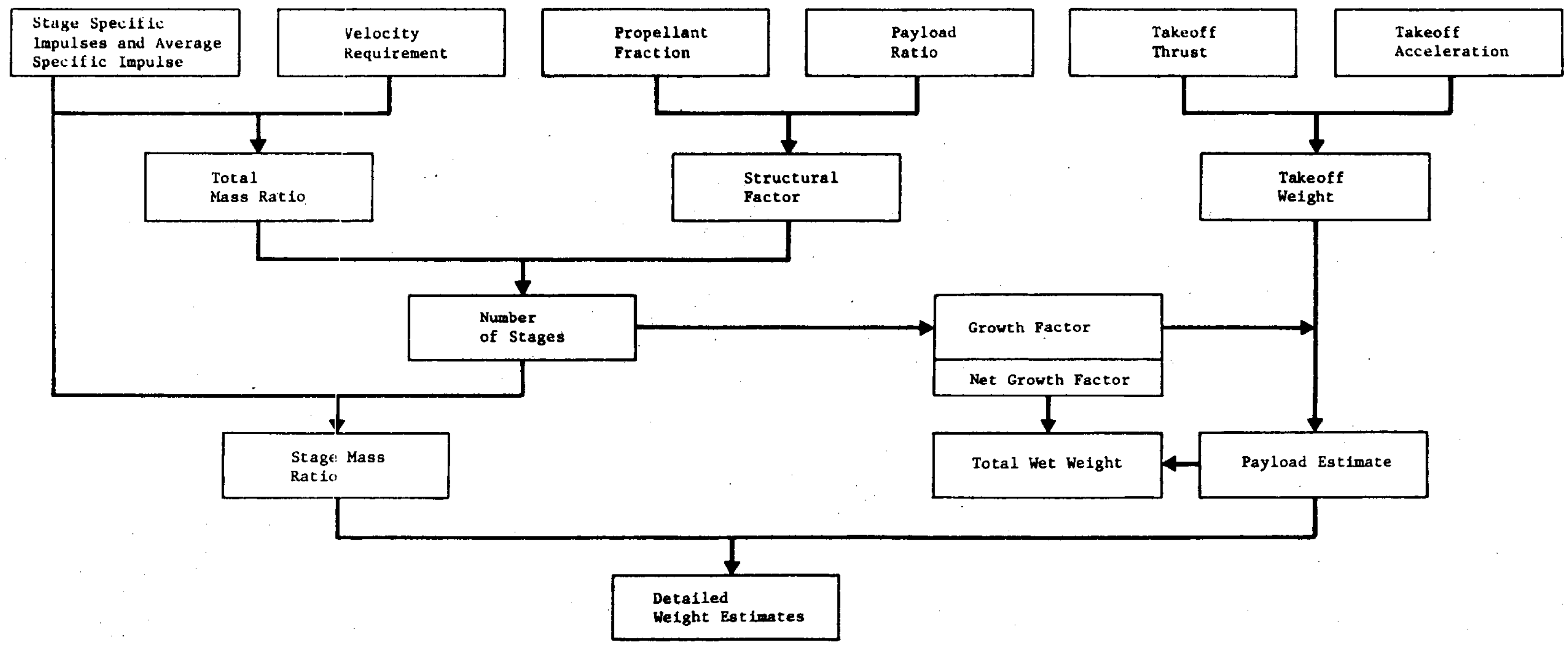



*Figure 16 Vehicle Performance Development Activities*

1) Act as lead discipline in defining the mission flight path and sizing of performance requirements for vehicle subsystems.

2) Develop simulation model of the system performance in all mission states.

3) Determine vehicle system performance requirements ($\Delta V$, accuracy) for the payload/mission.

4) Determine environments resulting from the system's interaction with atmospheres and planetary physical properties.

5) Provide the simulation module for examination, sizing, and optimization of vehicle performance parameters.

6) Evaluate performance effects on payload.

7) Determine performance capability margins.

8) Provide the means for vehicle system loads determination.

9) Provide the means for determining stability and control characteristics and requirements.

10) Specify the coordinate system flight mechanics models, computer programs, language atmospheres models, to be used in performance analysis of all system elements.

11) In conjunction with system safety, provide performance analysis of abort and hazard conditions.

12) In conjunction with structures discipline, perform staging analysis.

13) Define reference trajectory to be used for system definition/design.

*Propulsion (Figure 14, Item 2)*- The propulsion subsystem provides the thrust energy necessary to achieve required flight path trajectories and to control the vehicle orientation and attitude during the mission. The propulsion subsystem is integrally related to a number of other vehicle subsystems and must be considered in the sizing of these subsystems. It is because of these interrelationships and interfaces with other subsystems and the criticality of the propulsion subsystem to mission success that the configuration of the propulsion subsystem is a systems engineering activity.

The primary impact of the propulsion subsystem upon the design (performance) of other subsystems is on the vehicle structure and flight controls. The structures subsystem provides the structural support to house the propulsion subsystem and, more importantly, adequate structural rigidity to transmit propulsion force along the directional axes, while staying within tolerance for distortion and bending moments.

The flight controls subsystem is dependent upon thrust (thrusters) provided by the propulsion subsystem to control the attitude of the vehicle as well as the line of thrust when the main engines are firing. The systems engineering functions that are performed during the development program follow.

1) Determine the program schedule milestones such as integrated testing schedule, hardware delivery schedule, etc. This will affect the selection of the propulsion concept because major components of some concepts may require new technology or requalification.

2) Establish mission success criteria and operational safety requirements. This impacts the propulsion concept selection by indicating the type of components that the selected subsystem will require, level of redundancy, safety factors that must be met, and at various stages of subsystem development, test requirements to verify that the all requirements are, in fact, being met.

3) Develop specific functional performance requirements for each of the mission states. This affects component criteria and selection, and the subsystem development and qualification test requirements.

4) Determine external environmental levels in terms of pressure, temperature, and radiation that must be considered during the propulsion subsystem selection and development.

5) Establish physical envelopes and mechanical and electrical interfaces that will impact the propulsion subsystem selection.

6) Determine GSE and facility requirements.

7) Identify alternative propulsion concepts and configurations that meet the mission requirements.

8) Perform trade studies and select a single propulsion subsystem concept.

9) Analytically verify that the propulsion subsystem will provide the energy required for the mission.

10) Integrate the subsystem preliminary design with other vehicle subsystems and system elements.

*Flight Control (Figure 14, Item 3)* - The flight controls discipline is responsible for conceiving and designing systems for controlling the flight path and attitude of the vehicle as dictated by the guidance subsystem. This subsystem is closely correlated with guidance, propulsion, and vehicle structures performance, and because of this the analytical design of the flight controls is a systems engineering activity. The purpose of the flight controls system is to transform guidance commands into usable steering commands to control forces and to stabilize the rigid-body dynamics of the vehicle without exciting other vehicle characteristics that could produce excessive loading conditions.

During early conceptual studies, the design effort is aimed at selecting a type of system that meets mission requirements. Once the vehicle configuration, propulsion, and aerodynamics of the system have been determined, the rigid-body mode is analyzed and the constant gain configuration that stabilizes the vehicle is determined. As the vehicle structure definition proceeds and preliminary knowledge of the vehicle loads due to wind disturbances, thrust misalignment, propellant sloshing, etc is obtained, an initial analysis of the stability and control problem is made and the hardware impact is incorporated in the flight controls design.

The correlation with guidance, crew operations, propulsion, and electrical sequencing systems includes both performance and design considerations. The performance of these systems is interrelated in achieving a desired flight path trajectory and accuracy. This means that these systems describe a performance problem that must be solved as a combined effort of these disciplines. Because of the interrelationship with these disciplines in achieving system performance capability, the flight controls concept, definition, and design is a systems engineering activity. The specific system functions for this discipline follow.

1) In conjunction with the mission performance and definition team, examine the mission modes and determine the flight team, examine the mission modes and determine the flight control steering stability and attitude requirements that must be met. This analysis establishes the specific problems that must be solved, first analytically with a control scheme and, secondly, with a hardware design that implements the scheme.

2) Based on mission requirements, develop alternative scheme and hardware concepts, and describe them sufficiently to determine that each is feasible and will permit qualitative and quantitative comparison. The study criteria provides the selection criteria that identifies the system attributes and their relative importance.

3) Compile system design and performance requirements from central systems and other design groups applicable to the flight controls subsystem, and develop criteria for design definition.

4) Develop performance and design interface definitions in functional form; where significant system impact is identified, develop design solutions.

5) Support, as required, intercenter, intercontractor working groups for interfaces, crew/mission operation, verification, etc.

6) Develop analytical methods and models to permit assessment and synthesis of design solutions for each mission state.

7) Support configuration change board, program, and design review activities.

8) Provide inputs to central systems for statements of work, output specifications DRL/DRD for each program phase.

9) Implement system trade study requirements and criteria provided by central systems and participate in system level trade studies where flight controls is a factor.

*Guidance (Figure 14, Item 4)* - Guidance is concerned with the long range aspects of the flight path that an airborne vehicle must follow for a successful mission. The guidance discipline has the responsibility for defining the guidance and navigation requirements for attaining these flight paths and then synthesizing a hardware and software solution that best meets these requirements.

This involves defining the mission flight path(s), determining the navigational system (inertial, celestial, radio) to be used in determining methods of sensing flight path deviations and generating guidance command signals to activate the flight control system. As shown in Figure 14, this discipline activity involves the requirements from other design disciplines and systems engineering. The guidance solution must consider all of these requirements and satisfy them. The systems engineering functional activities can be classified in terms of system performance, requirements analysis, synthesis and integration. The first of these is the interaction of the guidance discipline in the mission analysis and determination of the guidance and navigation requirements for system accuracy. The requirements analysis is the determination of the total system requirements that must be satisfied by equipment and software provided by the guidance discipline. The systems engineering activities in synthesis and integration are those involving selection of a solution that best satisfied the mission/system requirements and integrating the guidance subsystem into the system.

The systems engineering activities performed by the guidance discipline follow.

1) As a part of the system performance team, determine the guidance and navigation accuracy requirements.

2) Develop guidance law equations for candidate guidance concepts.

3) Perform concept trade studies to determine mission feasibility.

4) Collect/compile and analyze total mission/system element/subsystem requirements affecting guidance and navigation.

5) Postulate design definition solutions to meet the system requirements.

6) Perform trade studies using system selection criteria.

7) Participate in system performance and design trade studies in which guidance is a factor.

8) Support, as required, program and system design reviews.

9) Participate in interface working groups and panels to assure the complete identification and solution of functional and physical interfaces.

10) Develop guidance error analyses to verify system accuracy capability.

11) Implement documentation requirements defined by central systems engineering.

12) Provide inputs to statements of work, system specifications and development plans that affect guidance and navigation, performance, design, and verification.

*Structures (Figure 14, Item 5)* - The systems engineering functional activities of the structure discipline are to configure a structure that supports and houses the payload. There are two aspects of structures design that have system implications. These are configuration design and system performance.

In the concept and configuration design phases, the structures group is the focal point for conceiving and configuring a structure that in size, shape, and arrangement adequately houses and protects payload elements. The structures activities represent the design integration function that takes as inputs the estimated size and mass properties of payloads and system conceptual decisions, such as number of stages, and conceives a structural configuration that is feasible in terms of size, shape, and strength. The term payload is used in the sense that all subsystem elements, mission payload subsystem, and vehicle subsystems are all payload elements.

The second system function performed by structures is to provide performance characteristics that are needed to size the system performance of other elements. The two system characteristics that impact system performance and the configuration of other elements are materials and loads.

*Materials* - The materials to be used in the structural design of payload elements must be identified as early as possible in the development program. The characteristics of these materials must be determined and compared with system requirements in terms of strength, rigidity, combustion point, ability to sustain combustion, outgassing toxicity, conductivity, etc. If the material selected is not on the current approved materials list maintained by the contracting agency, then the material must be tested and proved to be safe and meet all requirements, or rejected and another material selected.

*Loads* - The development of structural loads characteristics is the last system engineering functional activity of the structures disciplines.

Loads may be classified in accordance with their origin or distribution. *Body forces* are distributed within the volume of a body proportional to its mass. They are gravitational, magnetic, and inertia forces if the body is in accelerated or curved motion. *External forces*, such as thrust, pressure, lift, drag, support or bearing loads, shock and vibration forces, are distributed over the surface of a body. *Internal forces* are caused by nonlinear temperature distribution or nonuniform response to heating in structures with different materials, and their distribution depends upon the temperature and material distribution.

Static or dynamic equilibrium and compatibility of displacements with geometry and boundary conditions are the basis of all structural analysis. Stresses and strains in a body are caused by the difference in distribution or inertia or mass forces and external forces. If inertia and external forces are not balanced, the body changes either its velocity or its direction of motion or both.

The stress distribution and intensity is a function of force distribution and intensity, body geometry, temperature, and materials. In some cases it is also a function of deformations caused by one of the above mentioned primary influences. The body, bent by nonuniform temperature distribution, changes local angle of attack, and thus the lift distribution. Furthermore, the thrust now acts on a curved beam, creating an overturning moment, and, Together with the eccentric inertia forces, also creates considerable bending moment over the entire body. This can lead to buckling of the missile as a free-free beam.

During its lifetime, a space vehicle and its components experience a variety of loads: assembly loads caused by its own weight, thermal differentials, residual stresses from forming, machining, welding and milling; transportation and handling loads as well as the dynamic loads of flight.

The structural loads analysis efforts is to provide structures characteristics in the form of --

1) structural rigidity
   (bending modes frequencies and shapes and node locations with respect to control forces);

2) propellant sloshing modes.

This is a basic systems engineering activity that provides analytical data for vehicle control system design. The control system's task is to impose control moments on the vehicle in response to guidance commands and to resist disturbance inputs caused by aerodynamic disturbances, thrust misalignment, etc. The objective of the automatic control system is to stabilize and provide attitude control of the rigid body dynamics of the vehicle while not exciting vehicle modes that could produce excessive loading conditions.

3) Dynamic load stability analysis to include transient load analysis at launch, ignition, and shutdown. At each point in the mission sequence, some of these properties are coupled mode shapes, frequencies, and damping; time histories of accelerations and beam load; time histories of model responses (model accelerations, velocities, and displacements); maximum and minimum load displacements and accelerations; statistical loads combination.

4) Model analysis to evaluate the dynamic characteristics of the total vehicle to determine vehicle and payload transient response loads and flight control system stability. These parameters include uncoupled booster modes; coupled total vehicle modes; cantilevered coupled payload modes.

In addition to the primary system activity functions of the basic structural loads analysis efforts, the following secondary support in the overall system design area is --

1) determination of transport and handling loads;

2) consideration of storage loads;

3) estimation of prelaunch loads;

4) analysis of launch loads;

5) reentry and recovery loads;

6) flight loads, including wind gusts.

Once the preliminary loads on a vehicle are established, the design process determines selection of materials, overall geometry, and detailed dimensions to properly transfer those loads or external forces to equilibrate with the inertia reaction forces.

Thus, the main structural elements of the vehicle are defined. These are fuel tanks, engine, guidance and payload compartments, and transition members such as skirts, thrust mounts, brackets, and fitting to connect with the main parts. The main parts of the structure consist of elements such as tension ties, columns, beams, beam columns, trusses, and rings supported on an elastic foundation, and involving straight and curved panels and shells of various sizes.

These basic elements are now analyzed and designed to carry the primary and secondary loads reliably, as well as to reduce adverse interactions with each other, in terms of body flutter, sloshing; vibratory, acoustic, and other dynamic and thermal effects.

In summary, the systems engineering activities associated with the development of the vehicle structures follow.

1) Perform an analysis of the structural requirements in terms of the payloads anticipated, the shape and configuration of the vehicle structure, and the sizing required.

2) Develop alternative concepts of the structures configuration.

3) Perform trade studies to select the structures concept.

4) Identify the materials to be used in the structures design.

5) Determine if the materials selected are on the approved materials and parts list maintained by the contracting agency. If the materials are not approved, and cannot be because of safety or reliability factors, substitute materials must be selected.

6) Develop structural loads characteristics of the structural configuration.

*Electrical (Figure 14, Item 6)* - The electrical subsystem serves as a central switchboard to provide all power and switching functions to the various subsystems. As such, unnecessary duplication and lowered efficiency must be prevented through integrated development of the electrical subsystem.

From the initial subsystem identification, the subsystem designers designate functional requirements schematically, as well as provide preliminary location and packaging requirements within the flight vehicle and associated support equipment. Primary concern at this point is to identify minimum essential requirements for the flight vehicle and necessary subsystem support functions to be provided through the support equipment.

Following these initial steps by the individual subsystem engineers, the electrical systems engineer can initiate the electrical subsystem integration efforts.

The common needs and interconnections from one subsystem to another should identify the electrical distribution system where all the functions are established, controlled, and distributed. Systems engineering here establishes itself as an efficient and essential part of the overall system, and a tool to assure the greatest flexibility for maintaining the latest design requirements.

In forcing the design of each subsystem to reflect the primary vehicle mission, independent relays, sequences, and power sources can be eliminated and these essentials provided for all users by the electrical system. This will simplify almost every unit and permit the subsystem designers to concentrate on their primary task, assured that the primary power and sequencing functions will be provided. The electrical system's design will effectively combine all requirements and provide a flexible and efficient service to the total program.

The interrelationship of the various subsystems dictates that the integration of all requirements into an electrical subsystem is a systems engineering task. The specific engineering activities performed during this task follow.

1) Perform the initial electrical subsystem definition based on mission and other subsystems requirements.

2) Combine the electrical requirements of each of the subsystems.

3) Determine the operational sequences required by the mission and other subsystems.

4) Prepare layout of the electrical distribution required.

5) Allocate electrical limits to the subsystems.

6) Identify alternative concepts and concepts to meet the electrical requirements.

7) Perform trade studies to select the electrical subsystem concept and configuration.

8) Develop electrical subsystem design standards and criteria.

9) Prepare end item specifications for the electrical subsystem.

10) Perform integration activities.

*Communications (Figure 14, Item 7)* - The communications subsystem for a typical space mission consists of all facets of communication between the spacecraft and ground stations, spacecraft to spacecraft to spacecraft, and intraspacecraft. This includes real time voice communication, television, telemetry, delayed transmissions, taped data, filmed data, and stored data for return in the spacecraft. Typical data that may be communicated includes engineering data (housekeeping), equipment checkout data, operational data, hardware status data and crew data.

The communications subsystem is greatly affected by the operational concept and modes of the mission. For this reason, the mission concept must be clearly defined before the communications concepts can be defined and evaluated.

The systems engineering activities performed during the development of a communications subsystem follows.

1) Determine mission operational environments such as the atmosphere(s) through which data must be transmitted, spacecraft orientations, length of mission, distance of mission, etc.

2) Determine the requirements that the communications subsystem must meet to satisfy the mission such as:

   a) User Requirements --

      1) Engineering data (housekeeping)

      2) Checkout data

      3) Operational data -- real time voice communication; experiment and spacecraft subsystems status.

4) Crew data

b) What measurements are required

c) How much data is required

d) Accuracy required

e) When is data required; real time or storage

f) Data capacity --

1) Real time transmission

2) Delayed time transmission

3) Data rate - bits, symbols

4) On-board processing -- coding, storage, compression requirements, selection, scaling, data

g) Environment

h) Reliability

i) Safety

j) Power at frequency (command process)

k) Antenna usage

1) Antenna requirements

2) Modulation

l) Bit error rate

m) Signal/noise

n) Code

o) Receiver characteristics

p) Display

q) Processing

r) Power, weight, thermal model

s) Cost

3) Determine the physical and functional interfaces that must be considered during the communications subsystem design. Determination of interfaces may cover the interrelationships between all subsystems and disciplines. Lower level interfaces, such as connector-to-connector or pin-to-pin, are the responsibility of the design groups and are the concern of systems engineering only as they affect subsystem performance.

4) Develop alternative concepts and configurations that will meet the requirements.

5) Conduct analyses and trade studies to select the communications concept and configuration. The trade studies are usually conducted by specialists in systems engineering, communications design, and the other disciplines that are involved. One of the most important systems engineering tasks is to identify the analyses and trade studies that are to be performed and coordinating these tasks until completion.

6) Select and define the communications subsystem based on the above analyses and trade studies.

7) Prepare end item specifications.

8) Perform preliminary design.

*Environmental Control (Figure 14, Item 8)* - As in other functions in central systems engineering, the definition and control of environmental requirements is an activity aimed at achieving consistent and complete results that best meet the mission requirements. The environments that have a significant bearing on the successful definition and design of a system follow.

1) Natural environments that affect the system;

2) Induced environments resulting from the system's interaction with the natural environment;

3) Environment induced on one system by another;

4) Environmental conditions arising from interaction of system elements.

The types of these environments can cover a wide spectrum depending on the mission, and the survival of equipments and crews requires a definition of these environments. Knowledge of environments that exist or are propagated in each mission state; i.e., prelaunch, launch, ascent, Earth orbit, etc, is necessary in designing protection or control elements. Examples of environmental conditions that may be encountered follow.

Natural Environment
  Planetary
    Atmospheric (including wind loads)
    Thermal
    Gaseous content
    Gravity
    Radiation belts
    Magnetic fields
  Space
    Radiation
    Meteoroids
    Vacuum
Induced Environment
    Dynamic
    Thermal
    Radiation
    Man
    Vibration
    Shock
    Humidity
    Thermal
    Radiation
    Acoustics
    Meteoroids

The interactions that make up the systems environmental requirements activity include --

1) examination of the system element in each mission state;

2) identification and quantification of applicable environments for each state;

3) examination of system elements interaction with these environments;

4) development of a design criteria to be used in the definition/design of the system element;

5) generation of data to define or refine environmental parameters.

In summary, the systems engineering environmental group is responsible for environmental criteria tasks as follows:

1) Establish and maintain the program environmental design criteria, including thermal vibration, acoustics, shock, radiation, meteoroids, planetary environments, etc.

2) Act as the single focal point for environmental criteria control, specification, discussions, and presentations to customer.

3) When the program environmental criteria includes analyses from other functional disciplines, thoroughly review, understand, and approve the input analyses.

4) Assure that the rationale supporting each environmental definition is correct and thoroughly documented.

5) Verify environments with analyses and measurements as required.

6) Establish conservative margins between actual conditions and design and test conditions.

*Ground Support Equipment (Figure 14, Item 9)* - Ground support equipment is required to support all on-module and off-module activities from development testing through launch of the final program payload. GSE equipment takes the form of test tools, deliverable GSE, and maintenance and handling equipment. Central systems engineering acts as the organizational focal point throughout the program to integrate all technical support requirements that require ground equipment, and to develop an adequate and cost-effective set of hardware and software to meet these requirements taking into consideration the program constraints (i.e., cost, schedule, using locations, etc).

Each of the design disciplines must identify the GSE requirements needed throughout the development and operational program. It is these requirements that dictate kinds and quantity of GSE required for the program. The specific systems engineering activities performed during the development of GSE follow.

1) Develop the overall GSE philosophy compatible with the program.

2) Establish the requirements for GSE.

3) Scope the extent of the GSE task; i.e, number of end items, types of equipment, cost, schedule, etc.

4) Develop a GSE requirements document.

5) Baseline a preliminary set of functional test requirements; i.e., pressurization, power, PCM format, data recording, leakage checks, handling, alignment, etc.

6) Develop alternative concepts to meet the GSE requirements.

7) Perform trade studies of the alternative concepts considering cost, development, commonality, existing equipment, and commercial equipment, utilization rates, using site compatibility, flexibility, etc, to select the GSE concept and configurations.

8) Define the selected concept and configuration.

9) Establish the logistic support equipment configuration.

10) Prepare GSE end item specifications.

11) Establish design requirements and perform preliminary design.

*Facilities (Figure 14, Item 10)* - Facilities encompass these ground based installations that are required for test, operation, maintenance, receiving and inspection, and launch area storage of flight hardware and associated ground support equipment (GSE). The purpose of the facilities program is to assure that all required facilities are available to the operating forces and supporting activities in a timely manner. Facilities planning is based on operations and maintenance analyses, equipment design drawings, specifications and other documentation necessary for defining types of facilities, locations, space needs, environment, duration and frequency of use, personnel interfaces, installation activities, training requirements, test functions, and existing facility applications. Facilities development requires integrated attention throughout all phases of the life cycle to provide positive coordination with other program elements. Because of this integrated relationship, the selection of the facilities concept and configuration(s) is a systems engineering activity. The functional activities that are performed in the development of the facilities configuration follow.

1) Define and evaluate facility requirements.

2) Prepare facilities concepts.

3) Perform trade studies to select the facilities concept(s).

4) Perform facility sizing.

5) Integrate the facilities preliminary design with other system and subsystem elements.

The definition of facility requirements must be established as quickly as the determination of operational and support requirements are known due to the lead time involved with procurement and construction of the facilities. Development schedules must consider construction delay experience on similar programs due to seasonal weather and other regional considerations such as labor, soil conditions, etc.

The specific systems engineering functions that are performed during the development of the facilities configuration follow.

*Define and Evaluate Facilities Requirements* - During the development of each of the systems elements, the requirements for facilities (launch, test, storage, etc) must be determined.

Based on the required operational capability and the gross support requirement, an analysis is made to determine what facility capabilities are needed. An integral part of this analysis is an assessment of facilities used to maintain similar systems and equipment. This action is based on available operational readiness performance experience data, gross system configuration and preliminary maintenance and maintainability assessments of support needs. The resultant estimates should define both existing facilities that may be used and those requirements needing further exploratory study. Criteria considered in these evaluations include --

1) initial facilities tradeoffs needed to define basing, movement, deployment, durations and frequency, etc;

2) ground rules for facility selection (e.g., considerations of required material resources by type, quantity, and location as well as construction force needs in terms of skills, numbers, and availability);

3) constraints to be considered (e.g., security, easements, ownership, etc.);

4) operations and support interfaces to be examined (tenancy concepts, deployment variations, combat contingencies, duration differences, and primary launch, test or operating base complexes along with support shops, personnel, storage, and administrative requirements).

*Perform Facility Tradeoffs* - System feasibility studies and support element tradeoffs are evaluated for their impact on current facilities. Facility tradeoff studies are conducted to satisfy new requirements, and the best approaches are selected for review and consideration in the maintainability and reliability tradeoff studies. For example, the tradeoff studies may include consideration of alternative basing modes (e.g., hardened versus dispersed, mobile versus fixed, land versus water), existing versus new facilities, different materials to be considered, and portable versus fixed power sources.

The several support alternatives are evaluated and the most favorable facility concepts selected for further study. Cost information, technical feasibility problems and high risk areas are identified.

*Establish Facilities Concept* - A facilities concept is selected on the basis of maintainability and reliability tradeoffs and system feasibility studies. This concept is reviewed for compatibility with the maintenance concept, and is included in the support concept formulation package as guidance for the facility plan requirements to be identified in the facilities plan requirements.

*Provide Facilities Plan Requirements* - Facilities plan requirements are prepared for inclusion in the logistics support plan requirements and the RFP. They include criteria for further development of --

1) real estate and construction specifications;

2) primary facilities such as materials, power and communications, water, access roads, and critical real property;

3) support facilities for ships, personnel, training, storage transportation, and administrative use;

4) critical research and test needs;

5) facility life cycle cost and budget estimates for the funding schedule;

6) host-tenant agreements for support requirements.

*Establish Facility Plan Evaluation Criteria* - Technical and management evaluation criteria and interface control methods must be developed for determining the facility contractors' responsiveness to the general facility plan requirements and engineering design specifications. As part of the overall support criteria, they include evaluation of --

1) functional performance characteristics of supporting facilities (e.g., installed equipments' reliability, maintainability, useful life, environmental design and transportability);

2) both general and definitive design and construction specifications, standards, and constraints;

3) detailed facilities concepts for nontechnical support (e.g., functional requirements, support policies, survival requirements and policies, etc) siting and layout (e.g., area plans and site plans such as access, paving and drainage, contours, quantity-distance criteria, etc), and civil, architectural, structural, mechanical, and electrical requirements;

4) funding, schedule, technical, and management control for those items requiring prototype construction and testing (e.g., critical installed equipment and environmental control, electrical, power, missile launch suspension, and other similar systems).

*Integrate the Facilities Preliminary Design With Other System and Subsystem Elements* - During the process of developing the facilities preliminary design configuration, the form, fit and function characteristics must be ascertained on a continuing basis, to integrate the facilities into the total system. This integration process must consider the requirements of other system elements such as payload, vehicle, and mission and crew operations as well as subsystem elements such as propulsion, structures, electrical, etc.

c. Summary

This section has presented the systems engineering functions that are generally performed by each technical discipline in order to develop an integrated system, and a description of the system engineering activities performed within each technical discipline to develop subsystems that meet specific objectives and requirements and, when integrated, result in a complete and optimized total system. Figure 14 shows, in matrix form, the relationship between the function performed by a central systems engineering organization and the technical disciplines during the development process. Each of the examples of the systems engineering functions performed by the technical disciplines describes what the discipline is, the impact on the total system, the major interfaces and impact on other subsystems, and a summary of the systems engineering functions performed by the discipline.

## C. INTERACTIONS IN THE DEVELOPMENT PROCESS

The previous sections were concerned with "what people and organizations do" in describing the systems engineering technology. This description included consideration of the activities as part of each development phase, but an overview is needed to place these activities in the context of an integrated engineering operation. As pointed out, the development process goes through concept, definition, and design phases. These are natural states for system development, and it is possible to describe them as distinct activities as long as it is remembered that they are continuous and correlated activities. The departure point of one phase is not necessarily a hard breakpoint for the next phase activity. The tools (analyses, simulations, models requirements documentation, etc) are in process of continuous development; expansion and revision and the identification of the end of one phase and the beginning of another can only be considered as a rough division.

The following sections describe the concept phase and the definition/design phases in terms of major activities within which systems engineering performs the functions described in the previous section.

### 1. Concept Phase

The purpose of the conceptual phase is to conduct the necessary mission and system studies and analyses, stimulate the need, exploratory and advanced developments, and establish the economic technical and scientific basis for use in making a conditional decision to enter engineering development. When it is determined that there is a National Space Program need and technological basis to begin conceptual design of a system, the conceptual phase begins.

Systems are visualized that may meet the operational requirement and may be within the technological state-of-the-art of the time period concerned. Whatever the initial mechanism, studies are conducted to develop conceptual systems to a point where the operational and technological functions and equipment for the system can be identified in some detail.

Conceptual studies are concerned primarily with the feasibility of conceptual designs or approaches. The concepts are closely scrutinzed and analyzed to determine whether they are suitable, feasible, and acceptable, and the most preferred concept is selected. There are two general types of concept studies:

1) a broad-scope operational analysis type of study aimed at identifying the best general approach to fulfilling the objective;

2) a system concept selection study that defines the general configurations of systems that could be developed and produced in the time period of interest.

The output of this program phase is study results that:

1) identify mission requirements to accomplish stated objectives;

2) identify general system concepts and recommendations of the preferred approach based on performance and operational characteristics, and program requirements and constraints;

3) define a set of performance and operational requirements;

4) identify preferred subsystem concepts and general requirements;

5) determine program milestones;

6) determine gross cost estimates.

Figure 17 shows the expanded functions that make up the concept phase. An examination of several conceptual phase efforts showed that the degree of detail varied widely from program to program. The variation was due in part to the nature of the conceptual effort. On programs that were "make from" existing systems, the results tended to be more definitive than conceptual definitions for which there was little related past experience. In other cases, certain functional areas were pursued to a greater depth because there is a strong inclination among engineers to do detail design or to jump to configuration decisions early in the development cycle. The results of this investigation have been normalized by referring to the fundamental objectives of the concept phase and the descriptions of each function reflect what should occur.

An examination of the functions in this phase showed that *all must be classed as system engineering activities*. As in any state of development, many different specialists are involved. The nature of the work determines whether their activities are slanted toward the total system or are aimed at the system elements level. All efforts in concept definition are focused on a system concept and determination of its feasibility to accomplish the mission objectives.

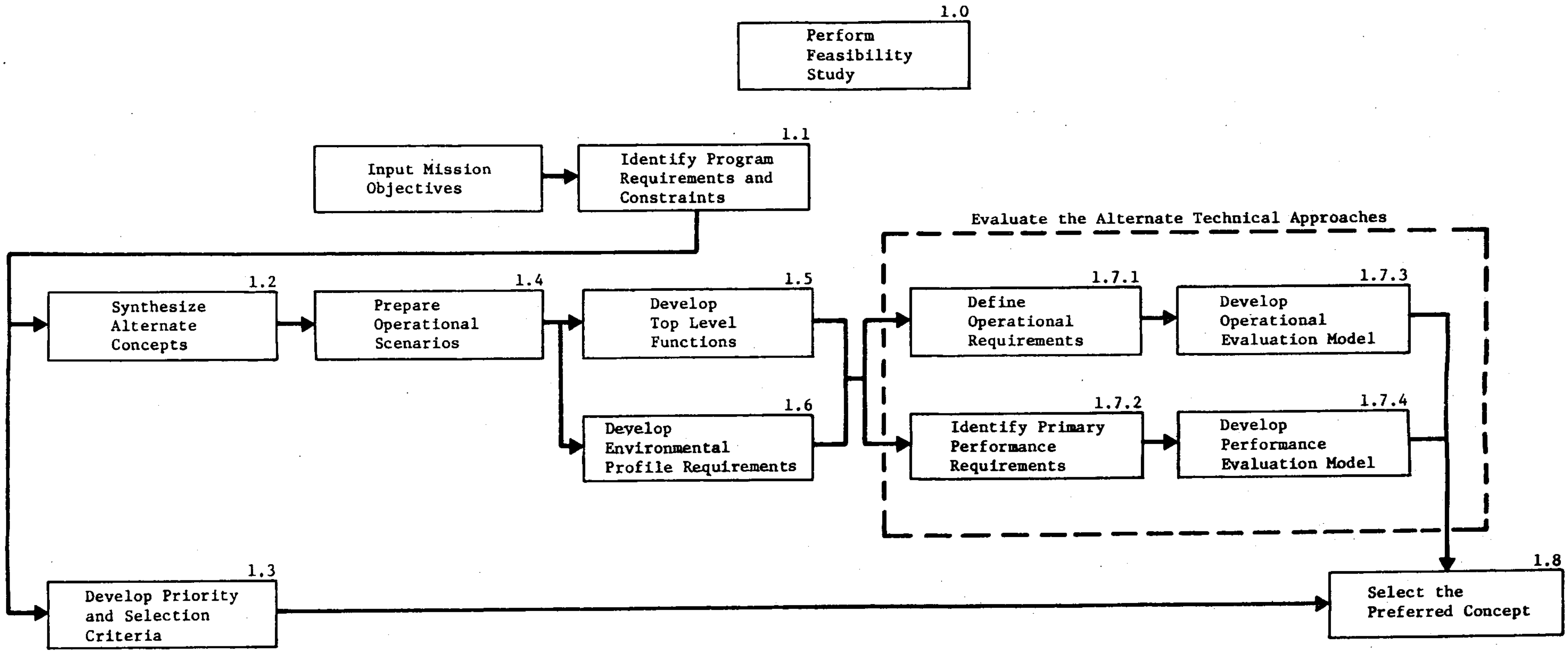



*Figure 17 Concept Phase Functions*

The following subparagraphs describe the functional activities of the concept phase with illustrations where needed to clarify the scope and content of functions.

*Block 1.1 (Fig. 18) Define Program, Technical Requirements and Constraints* - Prior to starting concept studies, it is necessary to analyze completely the nature and objectives of the required missions. The extent of mission definition provided will vary from program to program depending on the depth of earlier study efforts.

Known constraints that have a bearing on ensuing mission function analysis and initial system concept should be clearly established in the study guidelines and requirements.

This initial analysis includes an examination of systems that directly interface with or have a bearing on any system conceived to meet the stated objectives; i.e., a space rescue objective would require analysis of the system or systems served to determine operational, performance, and hardware requirements that would govern the concept of a rescue mission system. If the program includes a requirement to use or modify existing system elements, then these, too, would require analysis to identify the specific requirements that would form the basis for concept feasibility studies.

This functional activity as a whole represents the statement of primary requirements for the concept studies. These data will be changed and expanded as the study proceeds, but in their first draft they constitute a statement of the problem and the primitive requirements and constraints. This is fundamentally a systems engineering activity with inputs from other disciplines as determined by the particular objectives being examined.

*Block 1.2 (Fig. 18) Development of Alternative System Approaches* - The activities in this function represent the *initial* system definition effort that leads to generating those alternative approaches that will be presented as *technically*-promising concepts.

The activity of creative development of ideas or concepts to meet the gross mission requirements is performed in a number of steps, depending on the complexity of the mission. Generally, the project and system management define the states in terms of gross functions, and identify the types of systems that could accomplish the mission.

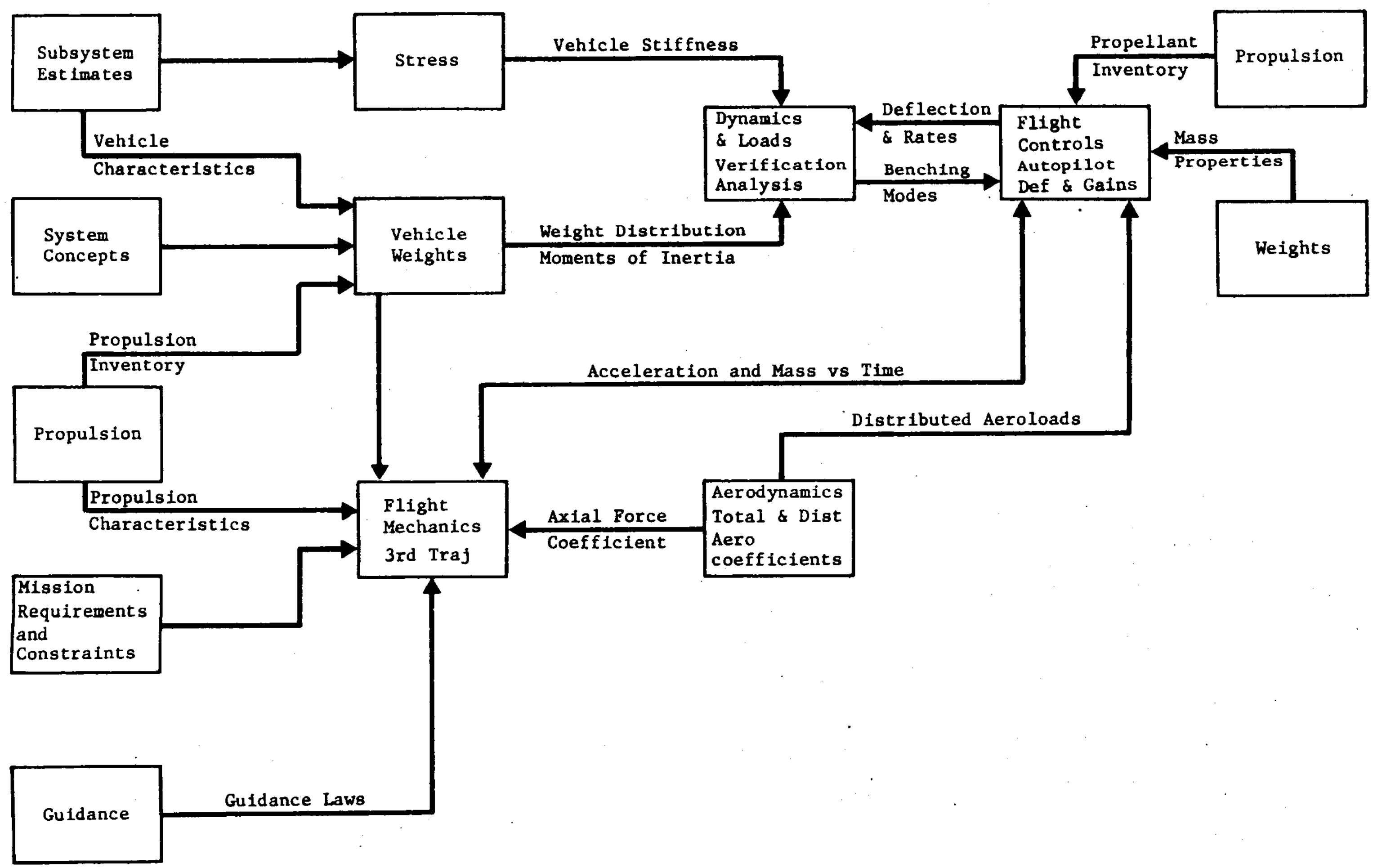



Figure 18 Vehicle Control System Performance Model

The types of scientific and engineering skills are identified and assembled into teams to study the states or mission phases. To give an example, an objective to perform a space rescue includes launch, attaining required flight path, docking and transfer, returning to Earth. These, states, the functions associated with each, and pertinent mission requirements, would define teams that would look for feasible system concepts.

Systems engineering activity leads each team of specialists to assure all concepts adhere to mission requirements, functionally integrates the study elements in each team, and achieves communication and compatibility between the various teams.

The activity begins with a detailed analysis of mission objectives and constraints to achieve complete exposure and detailed amplification of the problem. This task may require the development of a series of models to depict functions of achievable alternative technical approaches for accomplishing the mission. Each of these competing functional approaches is then analyzed in detail to determine the relative probability that performance requirements of the mission will be attained.

These alternative technical approaches are studied to translate objectives into performance requirements, constraints, and identification of major barrier areas as criteria for conceptual design of the system, subsystems and segments. The function performance requirements are documented in terms of inputs and outputs, environments, performance, time constraints, etc, in sufficient detail to identify types of subsystems required. These subsystems would, in turn, be studied to identify the concept that would prove feasible for those selected parametric data that are developed for use in examining the system performance for each concept.

*Block 1.3 (Fig. 18) Develop System Selection Criteria* - Since the object of this program phase is to identify alternative concepts, determine their feasibility, and select those that show the greatest program and technical merit, a decision criteria is needed. The relative value of various factors must be established as a means of determining the candidate concepts that have the greatest overall merit. This activity becomes relatively simple when there is only one overshadowing parameter such as total acquisition or total life cycle cost. However, when technical risk, development time, payload capability, duration of mission become important, priorities and a formula for assessing total worth may become needed. This functional activity represents the development of such information to be used in trade studies to identify recommended concepts. This activity is a systems engineering function. The approval of project management is required to assure that those responsible for decisions made in the course of the study concur with the criteria.

*Block 1.4 (Fig. 18) Develop Operational Scenario* - The study teams described in the previous function were concerned with concepts that could accomplish the mission. These teams also develop operational scenarios or profiles aimed at describing the way those concepts would work in performing the mission. These studies conceive of operational modes for time usage of system elements to accomplish the objectives and meet mission requirements; i.e., if a rescue mission has a reaction time requirement, then the readiness state must be examined and concept of operations together with performance requirements that meet the operational need.

The development of operational concepts and requirements addresses the availability, dependability, and verification aspects of mission requirements, whereas the conceptual studies aimed at conceiving system approaches (Block 1.2) were concerned primarily with capability objectives and requirements. These aspects encompass such scientific and engineering disciplines as logistics, reliability, maintainability, safety, test and checkout, facilities and specialists unique to the mission and system under consideration. Among these latter might be medical, crew geologists, etc. The steps in developing operational profiles and requirements include:

1) identification of the primary states and the associated mission requirements;

2) postulation or conception of alternative functional sequences for each state;

3) development of performance requirements in the form of parametric data for each function.

As this activity is a part of the synthesis of alternatives, it is an integral part of the work of study teams formed to perform the concept feasibility effort. Systems engineering *defines the specialists required, develops the study plan and integrates the activities of the various specialists involved.* Where mission requirements are changed or expanded, systems engineering *coordinates* these revisions throughout all study activities to assure that consistent alternative approaches are developed.

*Block 1.5 (Fig. 18) Develop Top Level Functions* - As system concept, operational modes, and scenarios are developed, the primary functions that must be performed to accomplish the mission are identified. This block represents the compilation of these functions for each of the alternative concepts, and correlating applicable mission requirements with each function. This step is the initial functional analysis that will continue throughout the development process. The purpose of this activity is to assure an orderly examination of the total mission and system elements by all members of the study team. The resulting information serves the function of giving systems management and the project an overview of the total mission in functional form, and permits examination of the proposed concepts for completeness and assessment of the compatibility of various facets of the conceptual design. These functional data are particularly important to operational concepts that address reliability, crew, maintainability, support, safety, etc, since these are not always described in as precise mathematical terms as are performance capability parameters.

Functional requirements of each system concept of the alternative technical approaches are depicted for all operational modes of usage in all specified environments. Each function is described with statements of beginning/end conditions to include inputs, outputs, and interface requirements from intrasystem/intersystem viewpoints. Functions are defined to assure indenture as part of the largest functions and arranged in their logical sequence so that any specified operational use of the system can be traced within the closed-loop cycle. Alternative operational cycles are also identified. When more than one system concept is evaluated, each is depicted and identified as above. Records are kept to reflect the rationale for acceptance or rejection of each alternative to permit traceability. Similar functions are cross-referenced to assure a common synthesis solution. Gross functions of each system concept are developed in sufficient detail to differentiate those performed by the system from those to be performed by subsystems. During this iteration all functional cycles (operation, maintenance, test, production, activation) are considered. While a detailed analysis cannot be made this early for all these functional cycles, concepts for all cycles are identified and described. Initial determination of skill levels and training requirements are identified and described.

The task of development of this functional analysis data is performed by the members of the study teams and is led by central systems engineering personnel.

*Block 1.6 (Fig. 18) Develop Environmental Criteria* - As each mission state is defined and as system concepts are conceived to operate in these states, the natural and induced environments are defined. This function represents the definition of these environmental data into basic criteria to be used in the evaluation of alternatives. The activity starts with the identification of the mission states. Studies are then initiated to define the natural environments within which all system elements will operate.

Such factors or ground winds, winds aloft, atmospheric properties, temperature ranges, humidity, etc, must be defined to serve as a basis for defining technical approaches and the reference conditions for comparing alternative concepts. There is a close relationship between the attributes, capability, availability, and dependability of concepts, and the environment. These functional activities are, therefore, highly iterative. As an example, the derivation of a statistical model of the Mars atmosphere influences the descent and loading profile and concepts of system elements for accomplishing these functions. The folloiwng is a representative list of the types of environmental criteria that may be involved in a system development. Not all of these are required to be defined in the concept phase since the extent of environmental information is greatly affected by the level of detail of mission and system. The system engineering task is to determine the requirements to realistically examine the feasibility of the system and operational concepts.

*Block 1.7 (Fig. 18) Evaluation of Alternative Technical Approaches* - Alternative technical approaches are evaluated in an iterative process that compares functional approaches against mission requirements, and the relative achievability and potential effectiveness of the alternatives.

In this step, the evaluations performed are normally limited by factors such as the depth of available background materiel and limitations in time, money, and study resources that affect the effort. A primary factor limiting the scope of evaluation is that it must be confined to data that is required to identify *technical* approaches.

The total system performance is assessed analytically by combing the performance characteristics of various system elements in a model (Fig. 18), performance can be compared to mission requirements to determine feasibility. In the concept phase, the models are simple parametric analyses based on estimates of element performance. Elements contributing to a vehicle capability might be size versus thrust, thrust versus weight, thrust versus cost, etc. These data for alternative types of concepts show the prime performance characteristics in terms of other program and performance variables. The system model brings together these factors to verify the integrity of combinations of elements and their compatibility with mission and program constraints. This shows a typical control system performance model for a vehicle system. The model brings together propulsion, guidance, flight controls, and trajectory concepts for evaluation. The gross system concepts of other subsystems such as electrical, communication hydraulic structures, etc, are represented as weight. Exercising this model will show feasibility and will also yield comparative data to select the most promising concepts. At this stage of development, the estimates of performance are highly uncertain and the feasibility must include determining reserve capability. The cumulative effects of dispersions and nonlinearities are unknown, and so reserve or margin are important factors in determining feasibility. These are identified and expressed in such terms as Δ velocity, weight, etc.

These performance evaluation, together with similar assessments of operational performance, constitute the system trade studies to compare alternatives. These analyses make the comparison in terms of:

1) overall configuration and equipment arrangement drawings (details of structure and equipment sufficient to show feasibility);

2) estimates of loads and load paths (size of major structural elements and selection of materials);

3) estimates of weight, center of gravity locations, mass moment of inertia, etc, where applicable;

4) gross mission requirements, parametric analysis, environmental profiles, crew size, mission duration and physiological requirements, performance, flight mechanics, gross cost and mission effectiveness analyses (Present data parametrically.);

5) interface requirements and major technical problem areas;

6) parametric data and tradeoff between various subsystem concepts (i.e., fuel cells, batteries, solar cells, etc);

7) preliminary estimates of mission success, crew safety, and reliability appointments among subsystems;

8) experiments and support equipment grossly defined and integrated.

Iteration in the study is accomplished as required to change, clarify, extend, and evolve alternative technical approaches into conceptual candidates. All reasons for decisions are carefully documented to permit traceability in follow-on system engineering activities.

This step is completed when all approaches have been evaluated and narrowed to those that appear to be technically most promising. The depth of evaluation at this time must be in sufficient detail to permit the preparation of a development plan.

The systems engineering activity is to perform the evaluation of the various parameters, apply the selection criteria to these data, and document the findings in system concept trade studies. These trade studies will identify all of the technical approaches evaluated, those eliminated as unfeasible and those deemed feasible and recommended for further study. Both quantitative and qualitative comparative data are presented to show the basis of selection.

Those alternative technical approaches that survive this initial iterative system development phase are presented in the study results. The technically promising alternative approaches are graphically portrayed using a task analysis diagram supported by brief specific narratives describing work to be done sequentially, work to be done in parallel approaches, major technical barriers, cost estimates, estimated time required to meet objectives, priorities of approaches, critical performance parameters, and probabilities of technical success for each approach.

2. Configuration Definition

This effort involves detailed study, analysis and preliminary design of each alternative system concept. The object of these studies is to select a single system approach from those identified in the concept phase. These studies are based on mission requirements and constraints identified in initial conceptual studies, as well as the program and technical ground rules and constraints added at the beginning of the definition/design activity. The conceptual approaches shown to be feasible are subjected to capability, operational, and verification analyses to establish a system configuration design for each alternative. These studies encompass:

1) refinement of selected alternative concepts;

2) preliminary system design data (including preliminary systems specifications);

3) preliminary assessment of manufacturing and testing facilities and techniques;

4) identification of systems requirements for launch and operational support;

5) system and subsystem design-margins/safety-factor goals;

6) preliminary reliability assessment, requirements, and plan;

7) preliminary quality assurance plan;

8) preliminary test plan;

9) identification of advanced research and technology and advanced development requirements.

The primary functions that take place in definition/design are fundamentally the same as those in the concept analyses, since the engineering process of conceiving elements to perform functions that accomplish mission requirements does not vary. This design process results in sizing of system elements and verification by more detailed analyses of performance and operational factors. Figure 19 shows the functions that make up the definition/design effort and the activities associated with system element. Following is a description of those steps in the definition/design phase of systems development process.

*Block 2.1 (Fig. 19) Study Planning* - The first activity in this phase is the management function of planning, organizing and staffing the study team. Each organization involved in the definition/design phase will have participated in concept studies or performed equivalent studies to provide the same insight and understanding of the development problem. Therefore, the task for each organization is to expand the study team that performed the initial studies to permit a detailed configuration design of the mission, performance required, and system elements.

The inputs to the system definition phase are mission requirements, alternative system concepts and program requirements and constraints. Design decisions at the system, system module or subsystem levels will, in some instances, have been made in the concept phase. These decisions will appear in the study requirements documents as criteria. Other configuration decisions will have been left open and subject to selection in the alternative approaches.

This first step, therefore, is an analysis of the input requirements and constraints to compare them with those used previously. The result is an adjustment in mission guidelines, evaluation models, and other factors previously used.

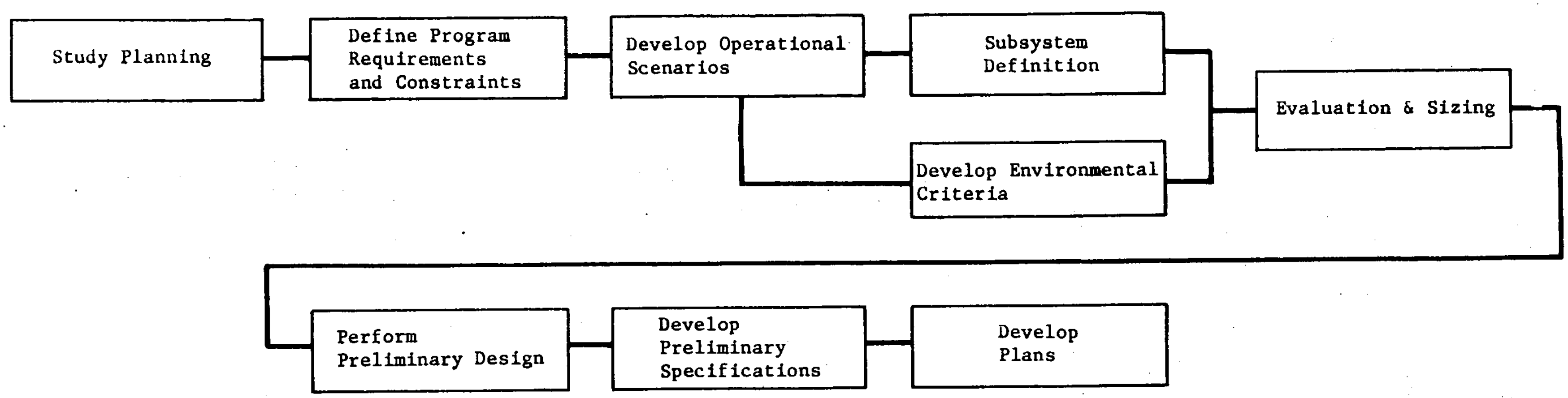



*Figure 19 Definition/Design Phase Functions*

*Block 2.2 (Fig. 19) Define Program Requirements and Constraints* - Based on analyses of study requirements, a study criteria is developed to control the study effort. This criteria defines--

1) selection criteria for trade studies;

2) the list of trade studies to be performed;

3) the baseline reference mission to be used for sizing and selection;

4) definition of the mission and development states that must be studied;

5) definition of the environmental criteria that must be expanded in the study;

6) definition of performance and design margins to be employed;

7) performance requirements from study guidelines;

8) system description from study guidelines and concept studies;

9) mission requirements from study guidelines.

This criteria document is a systems engineering effort and is maintained (revised and expanded) as the study proceeds. It forms the basis for studies in various portions of the system/ mission definition and serves as a data book for accumulation of results. The latter purpose provides management visibility to the overall study results.

Of the factors contained in the study criteria, the trade study criteria is of particular importance as it establishes the basis for decision-making during the study. In this criteria, specific operational areas of design features within which, or against which trade studies are to be made, are identified. Trade studies may involve revisions of system functions and performance requirements that can result in revised configurations of the system or specific end items.

Criteria for trade studies are expressed in terms of resources and system parameters. Examples of resources are funds, time, manpower, and skills. Examples of parameters are weight, mission length, reliability, maintainability, safety, vulnerability, and survivability. Criteria for measurement of system effectiveness are stated in quantitative terms where practical.

The criteria established for trade studies are related to the system measures of effectiveness with particular attention to "essential" and "desired" characteristics stated therein. Trade-off limitations are specified in relation to "essential" characteristics and performance requirements for operations, maintenance, test, production and deployment elements.

*Block 2.3 (Fig. 19) Develop Operational Scenarios* - Based on the study criteria, operational and mission functions and requirements are developed.

The initial function analysis that was performed during concept formulation is now iterated and expanded to lower levels to reflect for newly acquired information and directed changes. This analysis includes consideration, maintenance, test, production, and deployment functions to the level necessary to define concepts. A time requirements analysis is performed on time critical functions.

Mission objectives and constraints are reviewed and reexamined in relation to higher and lower order systems. A series of preliminary functional models are developed on as many levels as necessary to depict reasonably achievable alternative functional approaches. Each competing functional approach is then examined in detail to determine performance requirements associated with its function and the documenting of these requirements in terms of inputs, outputs, environments, performance constraints, time constraints, etc.

*Block 2.4 (Fig. 19) Subsystem Definition* - Each of the proposed alternative system concepts in the system development plan are expanded to acquire further understanding of functions, performance, design requirements and constraints. The impact of each proposed system concept on other elements of the total system are assessed, and these new concepts are used to expand further the functional model to identify lower indentured functions. This synthesis of solutions is accomplished only to a preliminary design level sufficient to assess design risk and to estimate development cost and schedule.

Schematics and layouts are used as tools to provide for visibility, traceability, and communication. They portray the functional and physical interfaces between system elements and aid in integrating performance requirements into specific system elements.

Facility end items, such as elevators, cranes, ramps, environmental control systems, etc are identified particularly in the case of command and control centers, missile installations, fixed repair facilities, strategic communication systems, etc.

The number and kinds of personnel for system operation, maintenance, test, production and deployment are identified in gross terms.

The facilities, personnel, training equipment, procedural data and periods of time needed for training purposes are identified in gross terms. Government furnished equipment (GFE) that constitutes constraints upon the system is identified.

In cases where the new system is one which is evolving from a presently installed system, or from a combination of presently installed equipments or systems, the performance requirements may have been generated from a study of existing capabilities. In this case, use of the functional models is subject to certain modifications in that the scope of the existing system may be fixed by mutual agreement between the developer and the user.

*Block 2.5 (Fig. 19) Develop Environmental Criteria* - As the development of system and mission information proceeds, the environmental definition is expanded from initial definition of natural and imposed conditions. These data are compiled from examination of the mission states and the system operating sequence in each state. Where conceptual studies were limited to preliminary assessments of environmental conditions, these definition analyses reflect a more detailed information based on better estimates of loads (thermal, shock vibration, etc). More complete models are developed based on these loads to determine compartment environments and the need for environmental control measures.

*Block 2.6 (Fig. 19) Evaluation and Sizing* - Based on expanded mission and operational analyses and environmental data, operational and performance models are expanded to evaluate the system configuration designs. This functional activity is the sizing of subsystem parameters, and developing time sequencing of functional events. In the mission and acquisition states, models are developed and exercised for:

1) capability - vehicle performance;

2) survivability - safety, life support, environmental control;

3) dependability - reliability, performance and design margin;

4) availability - readiness, launch on time, storage life;

5) operability;

6) transportability;

7) producibility.

The mission problems expressed as the functions to be performed and the functional requirements are expressed analytically in time of the performance parameters of system elements. The models are exercised to size the performance requirements into a set of allocations that satisfy the mission requirements, are feasible design requirements, and are optimum from a selection criteria point of view. These models are expansions of those developed in concept studies and new models developed to examine system aspects not previously examined. An example of this is the modeling of a launch vehicle performance capability. In early studies, a three degrees of freedom trajectory model provides sufficient visibility to determine feasibility of attaining a given payload-orbit capability in terms of thrust, weight, accuracy, etc. In system definition, the model would be expanded to reflect a distributed body. Subsequently, in preliminary and final design the model would be expanded to six degrees of feeedom and dispersions of parameters used to refine the performance analysis of the systems ability to perform the mission.

The basic elements of modeling of performance factors are the analytical expression describing the mission in terms of physical parameters such as time, energy distance, mass properties, environments, geometry, etc. The resultant performance relates to performance parameters of subsystem elements of the system. The parametric data that feeds the system performance models are parametric data resulting from performance analyses of the subsystem involved. These subsystem performance analyses are also performance models for the concepts previous studies have shown feasible. In the example of a launch vehicle sited above, some of the subsystem performance models would be:

1) guidance - guidance equations and error analysis;

2) propulsion - performance model and error analysis;

3) structure - load analysis;

4) aerodynamics - aerodynamic equations - heating analysis.

*Block 2.8 (Fig. 19) Perform Preliminary Design* - Once systems performance analyses and determination of allocations to subsystems is accomplished, the selected system element and subsystem concepts are expanded to a preliminary design. The preliminary design is a detailing of each system element and subsystem in terms of configuration, function, design characteristics, and interfaces.

Preliminary design is aimed at describing the hardware, defining design and functional requirements and describing functional and physical interfaces. The input, in each case, is the system performance requirements. The factors listed above describe all factors that must be considered in preliminary design. Each of these factors is described below to show the data developed in preliminary design.

*Configuration* - Size, weight, equipment elements, outboard profiles, location interrelationship of elements, materials, construction methods, arrangement of elements. These are described in block diagram, schematics, arrangement drawings, isometric drawings, layouts.

*Functions* - Operating description, sequencing, mission modes, power requirements, environmental conditions, method of checkout, verification methods, measurement lists. These data are in the form of operating descriptions, timelines, logic diagrams, performance parameter profiles, functional descriptions and functional requirements.

*Design Characteristics* - Reliability allocation, safety criteria, maintainability, allocation, design margins. These are described in terms of numerical values.

*Interfaces* - Functional and physical interfaces with other subsystems and modules and other system segments covering mechanical, electrical, environmental, operating, handling. These data are described in preliminary interface documents which contain descriptions, parametric data, parametric value, arrangment schematics and drawings. The interface definition is the identification of complex interrelationships between fundamental building blocks, subsystems, and all other elements of the system. The total system can usually be defined in descending sets of complex elements as in Figure 20.

The interfaces of a subsystem are the sum total of its interrelationships with all other subsystems and elements. Preliminary design must develop (identify and quantify) these interfaces. Where quantification is not possible, because of lack of information, the minimum requirement is the definition of the functional interface. The decision as to whether any interface can be left in functional requirements form or should be carried to a solution is dependent on its impact on the system definition program cost and schedule.

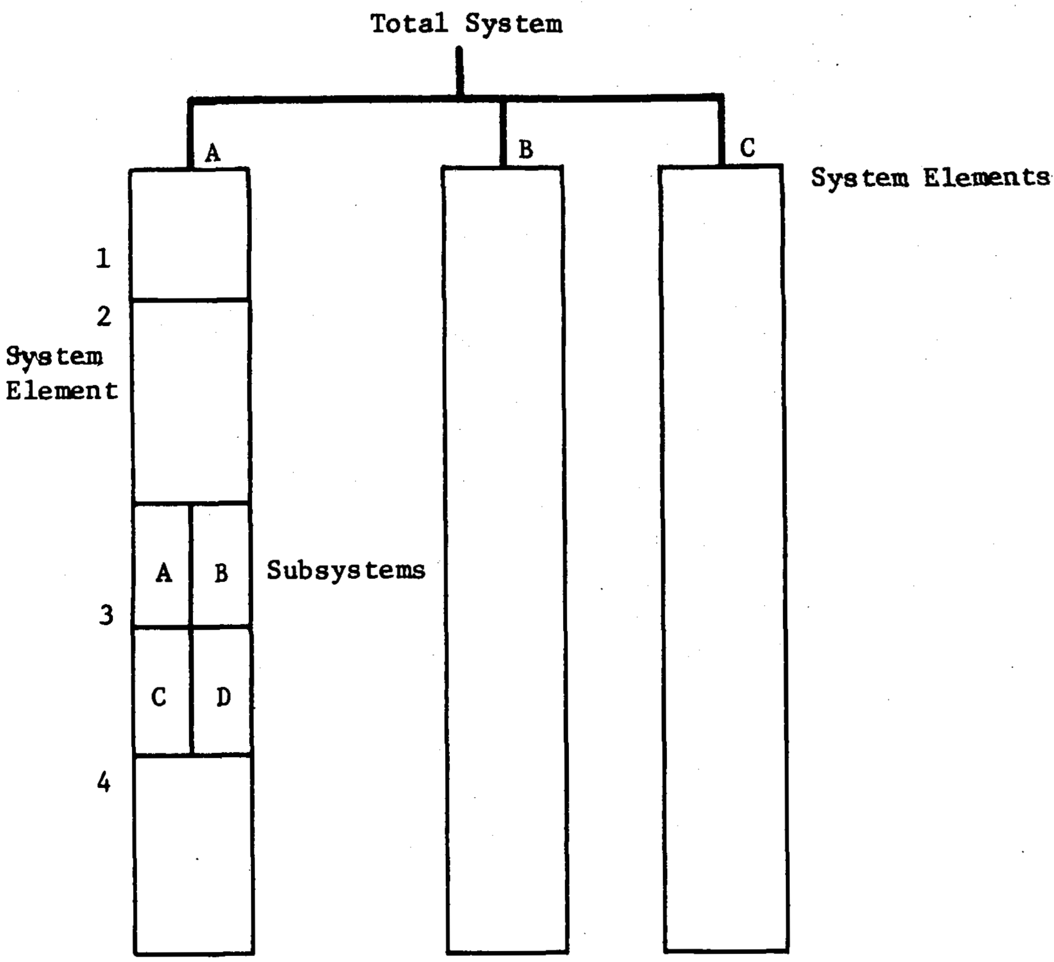



*Figure 20 Total System*

If a particular parameter has significant bearing on performance of either a major system element or on other elements, it would be quantified. If the sizing of the interface has significant cost impact to the agency or contractor performance of the development of a system element then, too, it should be quantified.

In subsequent steps of system definition and design, these interfaces are defined in ICDs at various levels, i.e., module to module, system element to system element, and system to system.

*Block 2.8 (Fig. 19) Develop Preliminary Specifications* - Preliminary system design data for the system and each system element is the primary technical output of the system definition phase. These data are combined at various levels of complexity to provide a coherent set of performance and design specifications of the system and its elements that have been conceived, configured, and sized to meet the mission requirements. The system definition results in a definition of the minimum set of specifications sufficient to describe the system configuration and the "design to" requirements for each element. The hierarchy of specifications needed to give a clear picture of a system depends on the complexity of the subject system. In general, a top system specification and a system specification for the major systems will be required to describe the system performance and design requirements that have been derived during this study phase.

Since system definition may involve study of more than one conceptual approach, the configuration design of each concept will result in system specifications. These will provide a basis for comparison and selection of the most promising concept.

*Block 2.9 (Fig. 19) Develop Plans* - The results of the definition/design activity are definitions of equipment, facilities, personnel, software, a functional description of how they work to meet derived mission requirements. The elements needed to perform the mission are described in preliminary specifications and in plans. Plans document actions required to implement the requirements derived during the system definition and design phase. Examples of these documents are the reliability plan, test plan, quality assurance plan, logistics plan, and configuration management plan. Each of these plans will include the following types of information:

1) related organizations and responsibilties;

2) methodology - methods and procedures to be employed;

3) means for review and controlling the activities;

4) identification of coordination and control of various organizational activities;

5) reports and documentation to be used;

6) milestones and schedules;

7) identification of support and facility requirements needed to implement the activity;

8) flow charts identifying the sequence of events;

9) description of detail approaches to be employed for each major activity;

10) identification of criteria to be used in performing the functions and judging performance;

11) records, data, and approaches required in performing the functions.

These data for each of the plans listed above describe "how" the function will be performed.

### 3. Summary

In summarizing, this section has presented a view of systems engineering in terms of the integrated activities that make up each phase. This description emphasized two things. The systems engineering objectives are accomplished by a strategy that involves control integration and evaluation of the technical efforts of all disciplines. The composite of the activities described in Section V.B are planned so that the result at the project level constitutes a technical requirement management to assure that results are stated and maintained as a consistent set of things. The second point emphasized in this section is that the process of development is not a set of distinct and separate phases, but is a continuous evolution to greater and greater detail requirements and description of the system. Phase definition for contractual purposes is not necessarily an accurate description of the degree of system definition.

D. SYSTEMS ENGINEERING OPERATIONS

In the previous sections, the description of systems engineering was treated in terms of roles and responsibilities and development process activities. This treatment addressed the interrelation of systems engineering with elements of the system and with stages of development. These sections, B and C, described a three-dimensional condition, two at a time; the three factors are systems engineering activities, systems elements, and system development activities (in time). This concept of the problem is shown in Figure 21 with the interactions described in previous sections identified. These three planes were covered separately to give a clear picture of each of the factors. The folding of these three views of systems engineering on a single plane is desirable because it gives a composite view with respect to time that is important to understanding system engineering functions.

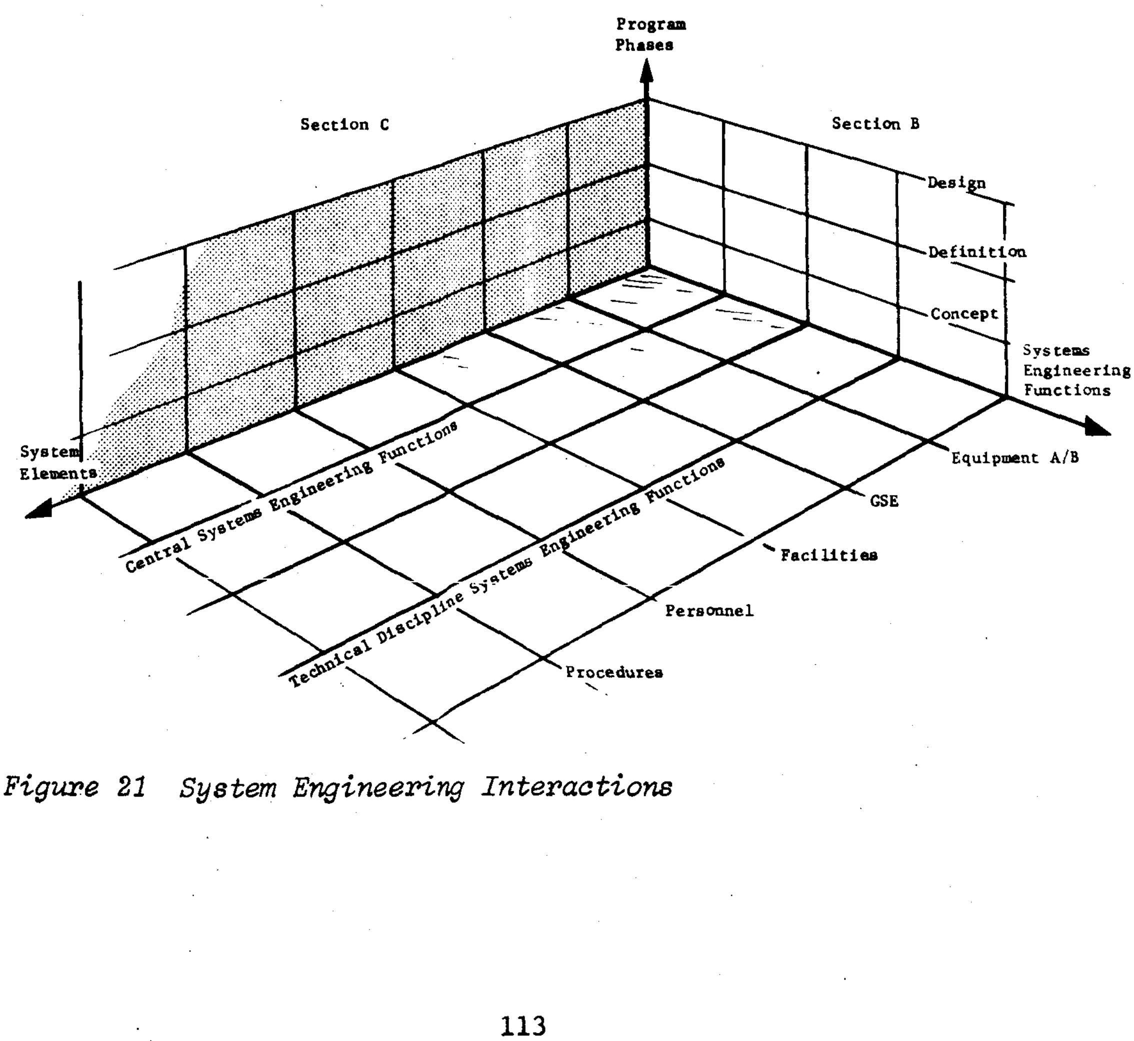



*Figure 21 System Engineering Interactions*

Figure 22 shows a composite set of activities that occur during the definition/design phase. In this figure, the interaction of central systems disciplines and technical disciplines is shown at each point in the development process. The most important feature shown in the figure is the system requirements and definition baseline that drives the development process and represents the baseline control of system requirements. As can be seen, this baseline is a source of requirements at each point in the development process and is continuously updated and maintained as decisions are made. The requirements baseline in Figure 22 is identified as a heavy dark line near the top of the diagram.

Figure 22 is an over simplification in the sense that, as a single view, it implies no organizational complexity. In practice, there would be a series of parallel flow charts for a multiorganization program, each addressing its portion of the program and its interfaces with other segments. This composite diagram demonstrates the complexity that exists within a given system element as well as between system elements, and shows the need for continuous involvement of central systems engineering and the disciplines it represents to emphasize the total system.

In the following discussion, the activities of Figure 22 are identified and described. In the horizontal axis, the requirements, disciplines, activities, and system elements are identified as follows:

A. Central Systems Disciplines;

B. System Integration Requirements;

C. Technical Disciplines;

D. Activities;

E. System Elements.

These activities are interrelated as will be seen upon examination of the diagram, and the output of one activity affects the performance of another activity. This emphasizes the importance of the system requirements baseline that drives the development process and provides baseline control. It is the central source of requirements that affects all elements of the system.

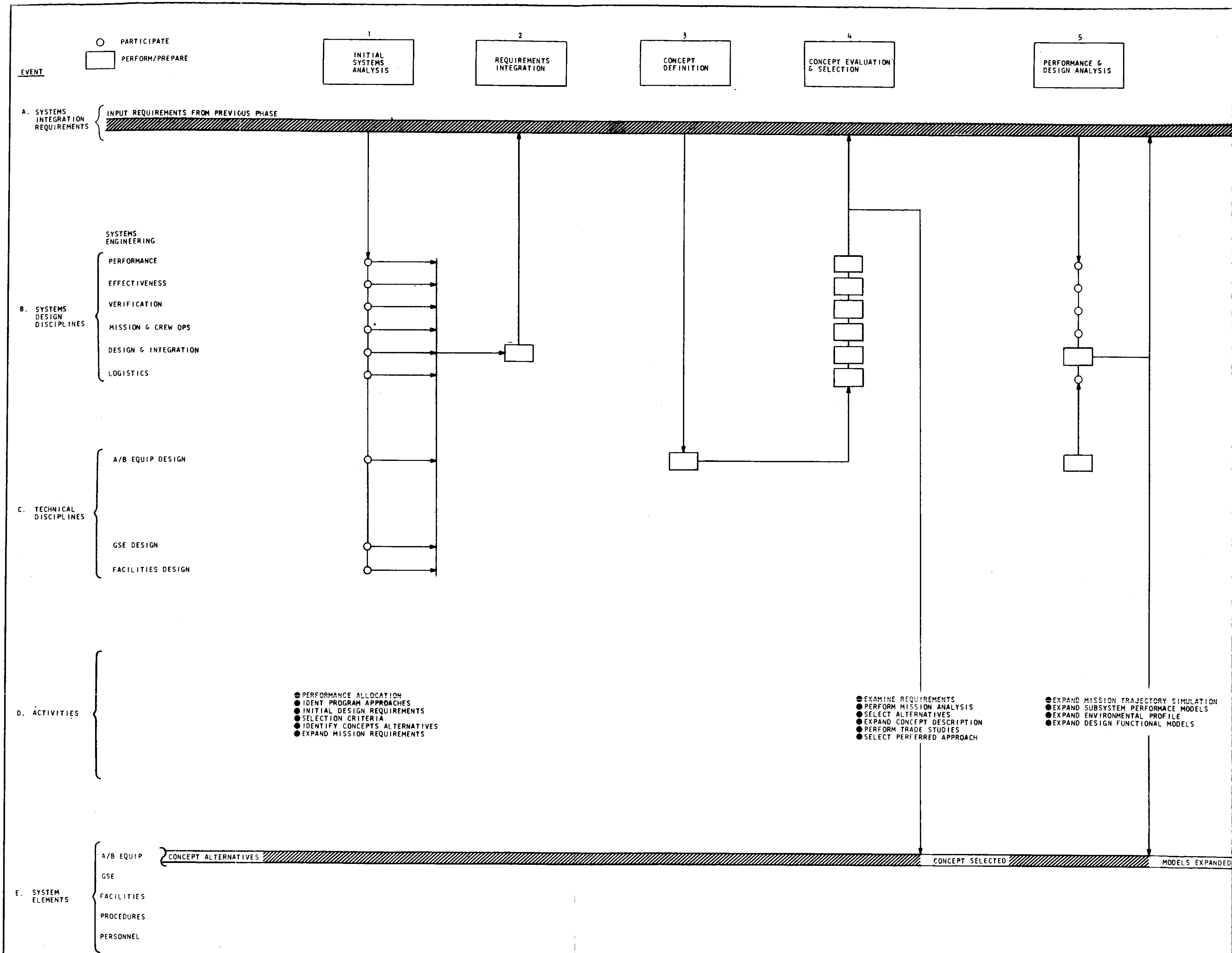
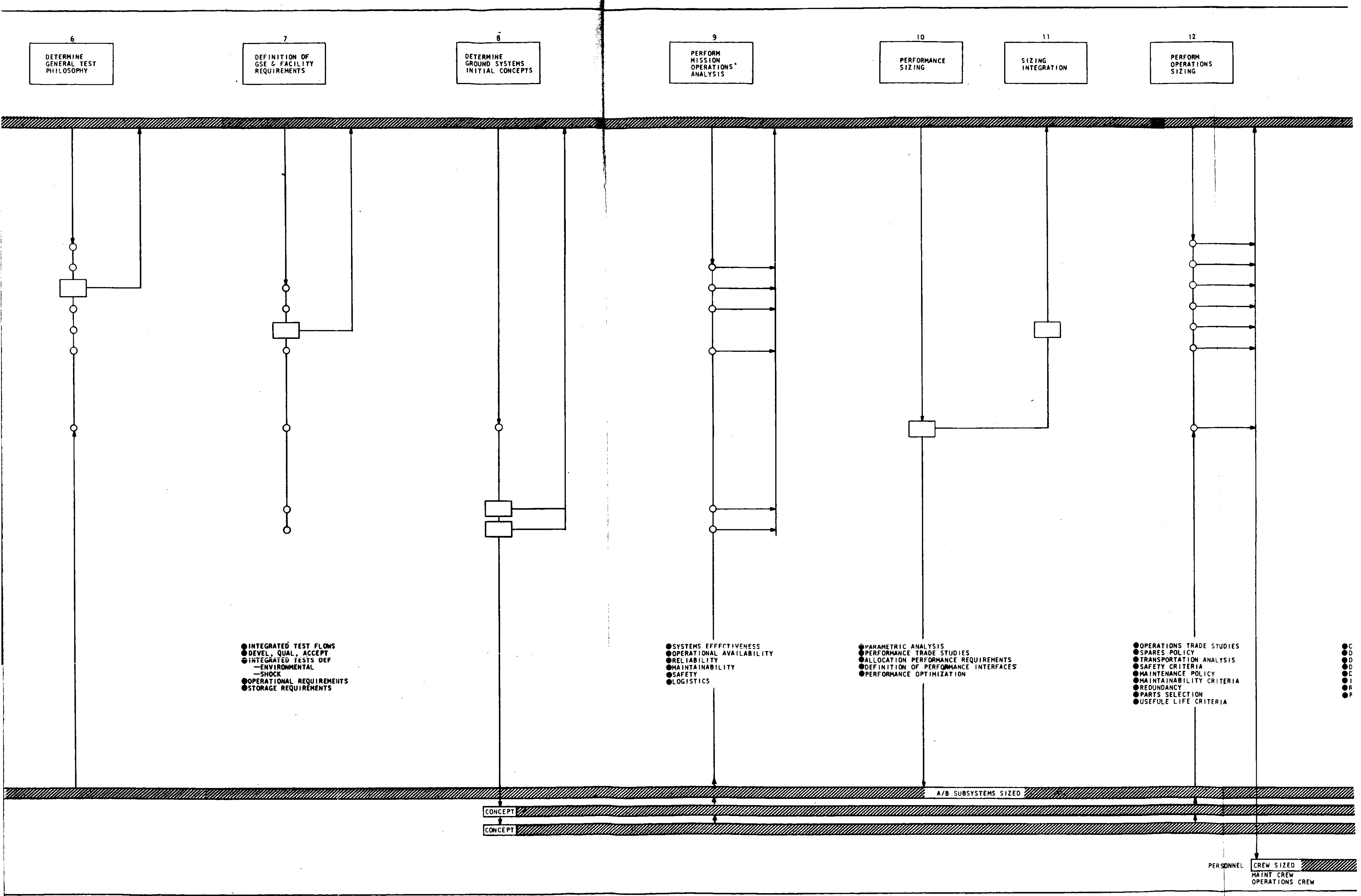



*Figure 22 Definition/Design Phase Activities*

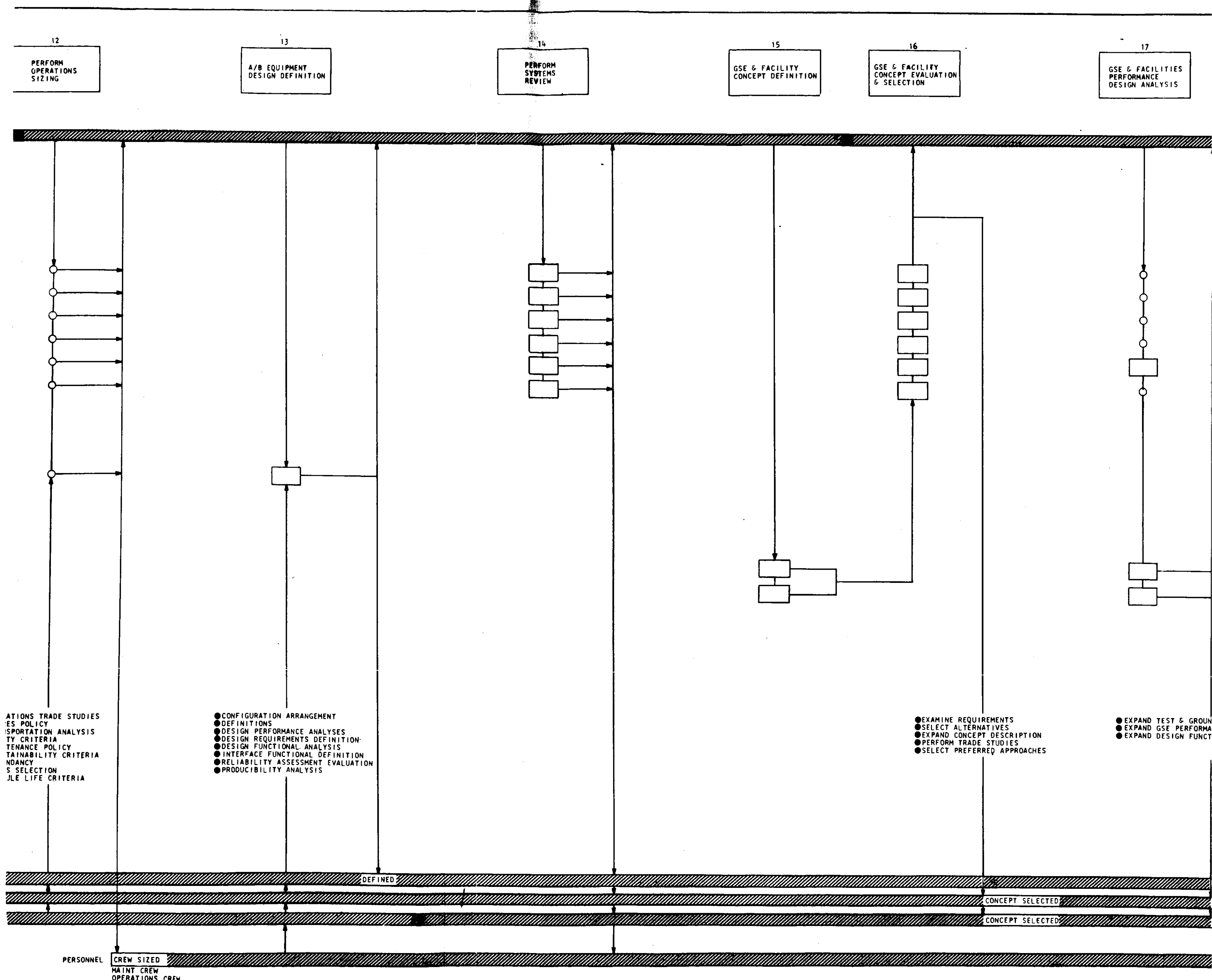


Fold-out 1



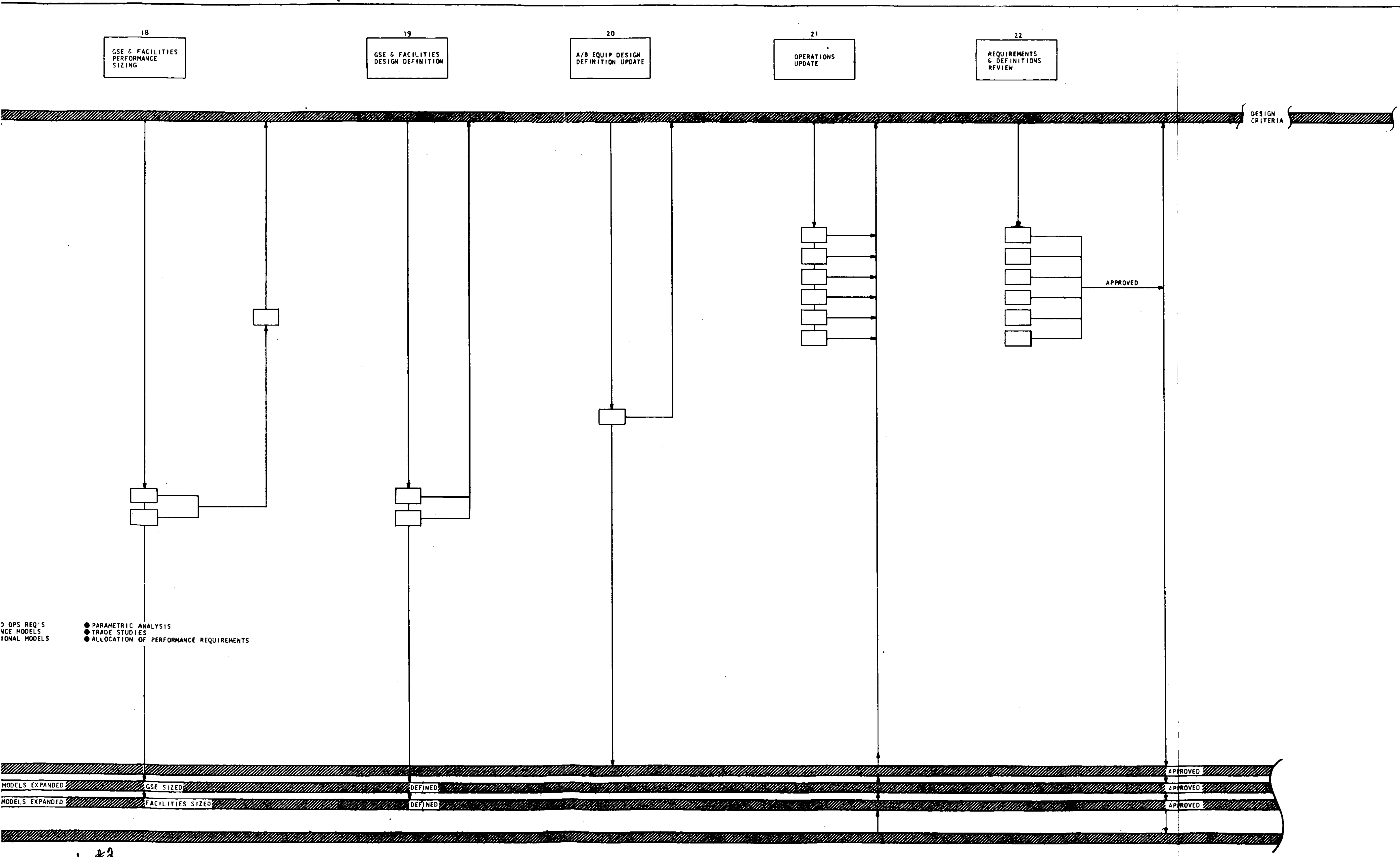
6
DETERMINE GENERAL TEST PHILOSOPHY
7
DEFINITION OF GSE & FACILITY REQUIREMENTS
8
DETERMINE GROUND SYSTEMS INITIAL CONCEPTS
9
PERFORM MISSION OPERATIONS' ANALYSIS
10
PERFORMANCE SIZING
11
SIZING INTEGRATION
12
PERFORM OPERATIONS SIZING
●INTEGRATED TEST FLOWS
●DEVEL, QUAL, ACCEPT
●INTEGRATED TESTS DEF
—ENVIRONMENTAL
—SHOCK
●OPERATIONAL REQUIREMENTS
●STORAGE REQUIREMENTS
●SYSTEMS EFFECTIVENESS
●OPERATIONAL AVAILABILITY
●RELIABILITY
●MAINTAINABILITY
●SAFETY
●LOGISTICS
●PARAMETRIC ANALYSIS
●PERFORMANCE TRADE STUDIES
●ALLOCATION PERFORMANCE REQUIREMENTS
●DEFINITION OF PERFORMANCE INTERFACES
●PERFORMANCE OPTIMIZATION
●OPERATIONS TRADE STUDIES
●SPARES POLICY
●TRANSPORTATION ANALYSIS
●SAFETY CRITERIA
●MAINTENANCE POLICY
●MAINTAINABILITY CRITERIA
●REDUNDANCY
●PARTS SELECTION
●USEFULE LIFE CRITERIA
A/B SUBSYSTEMS SIZED
CONCEPT
CONCEPT
PERSONNEL
CREW SIZED
MAINT CREW
OPERATIONS CREW


Fold-out 2



12
PERFORM OPERATIONS SIZING
13
A/B EQUIPMENT DESIGN DEFINITION
14
PERFORM SYSTEMS REVIEW
15
GSE & FACILITY CONCEPT DEFINITION
16
GSE & FACILITY CONCEPT EVALUATION & SELECTION
17
GSE & FACILITIES PERFORMANCE DESIGN ANALYSIS
ATIONS TRADE STUDIES
ES POLICY
SPORTATION ANALYSIS
TY CRITERIA
TENANCE POLICY
TAINABILITY CRITERIA
NDANCY
S SELECTION
JLE LIFE CRITERIA
●CONFIGURATION ARRANGEMENT
●DEFINITIONS
●DESIGN PERFORMANCE ANALYSES
●DESIGN REQUIREMENTS DEFINITION
●DESIGN FUNCTIONAL ANALYSIS
●INTERFACE FUNCTIONAL DEFINITION
●RELIABILITY ASSESSMENT EVALUATION
●PRODUCIBILITY ANALYSIS
●EXAMINE REQUIREMENTS
●SELECT ALTERNATIVES
●EXPAND CONCEPT DESCRIPTION
●PERFORM TRADE STUDIES
●SELECT PREFERRED APPROACHES
●EXPAND TEST & GROUN
●EXPAND GSE PERFORMA
●EXPAND DESIGN FUNCT
DEFINED
CONCEPT SELECTED
CONCEPT SELECTED
PERSONNEL
CREW SIZED
MAINT CREW
OPERATIONS CREW


Foldout #1




DEFINITION/DESIGN PHASE ACTIVITIES
FIGURE 22

Foldout #2

The vertical axis of the diagram shows events that occur during the development process, and the inputs and outputs of these events in or out of the requirements baseline. The diagram will be described in matrix fashion, i.e., line A, event 1; line A, event 2; line B, event 1; and so on. Initially, the requirements from the previous phase must be determined and distributed to all concerned during the definition/design phase.

1. Initial Systems Analysis

The first event is the initial systems analysis of the input requirements to aid in selection of the concept for airborne equipment (E-1). This is performed by the central systems disciplines as shown in B-1, and by the technical disciplines shown in C-1. The activities performed are those shown in D-1. The results of these activities are inputs to the requirements baseline of central systems engineering (A-1).

2. Requirements Integration

After the initial systems analysis of the input requirements has been completed, the results are integrated into systems requirements to determine the concepts selected for airborne equipment. The requirements integration event is shown in B-1.

3. Concept Definition

The alternative concepts for the system elements are fully defined so that selection can be made. This is shown in event C-3.

4. Concept Evaluation & Selection

Once the alternative concepts have been fully defined, they are elevated by central systems engineering and the best concepts for A/B equipment are selected (B-4). The activities involved in the evaluation process are shown in D-4. The concepts selected are then integrated into the requirements baseline (A-4) and the system element line (E-4).

5. Performance and Design Analysis

After the A/B equipment concepts have been selected, a performance and design analysis is performed by the central systems engineering and technical disciplines (B-5 and C-5). At the same time, the systems design and integration discipline performs an integration activity of the performance and design analysis results to assure that the concepts meet total systems suitability (B-5). These analyses and integration activities result in an expansion of the models used in the concept selection process (E-5) and in an input to the requirements baseline (A-5).

6. Determine General Test Philosophy

At this point in the development process, after the airborne equipment has been essentially determined, that initial thought is given to the GSE and facilities required. A general test philosophy is determined by the verification discipline of central systems with the participation of the other central systems disciplines (B-6). The general test philosophy developed is based on information obtained from the requirements baseline (A-6), the technical disciplines (C-6), and the system element models (E-6).

7. Definition of GSE and Facility Requirements

GSE and facility requirements are defined by central systems design and integration discipline with participation from airborne equipment design, GSE design, and facility design technical disciplines. These definitions are based on the requirements baseline data (A-7) and the activities of D-7.

8. Determine Ground Systems Initial Concepts

With the general test philosophy established and the GSE and facility requirements defined, the ground systems initial concepts are determined by the GSE and facilities technical disciplines (C-8). The A/B equipment technical disciplines participates in the determination of the ground system initial concepts (C-8). The results are input to the requirements baseline (A-8) and the system element line (E-8).

9. Perform Mission Operations Analysis

Once the GSE and facilities concepts are established, a missions operations analysis is performed by the central systems disciplines (B-9). The material in the requirements baseline (A-9), the information provided by GSE and facilities design (C-9), and the system element concepts and description (E-9) are used as the sources of data for the analysis. The activities shown in D-9 are the ones involved in the analysis. The results of the mission operations analysis are input into the central systems requirements baseline (A-9).

10. Performance Sizing

A performance sizing activity of the airborne equipment is conducted by the airborne equipment technical disciplines (C-10). The source of information used in the performance sizing activity is the requirements baseline. The result of this activity is the sizing of the airborne systems (E-10), and the performance sizing results are integrated in the requirements baseline. The activities of D-10 are involved in the sizing and integration process.

11. Sizing Integration

Based on the results of the performance sizing activity, the design and integration discipline of central system engineering performs an integration activity to assure that the performance sizing results are compatible with the total system concept (B-11). This integration activity must be performed before the sizing results are integrated in the requirements and definition baseline (A-11).

12. Perform Operations Sizing

An operations sizing analysis is performed by the central systems engineering and technical disciplines (B-12 and C-12) using, as the basis for the analysis, the source material contained in the requirements and definition baseline and information from the system element (E-12). The activities of D-12 are involved and result in the determination of the personnel required for ground operations (E-12). The results of the operation are also integrated in the requirements and definition baseline.

13. A/B Equipment Design Definition

The activities of D-13 are performed during the design definition. The source material for the design definition activity came from the requirements definition baseline (B-13) and the system elements (E-13). The outputs of the airborne equipment design definition result in the airborne equipment being defined (E-13) and integrated in the baseline (A-13).

14. Perform Systems Review

After the airborne equipment is defined, a systems review is held to determfine if the equipment, as defined, meets all requirements. The requirements and definition baseline (B-14) is the source of information for the systems review. The results of the systems review are integrated in the system elements (E-14) and in the requirements and definition baseline (A-14) for use in subsequent definition update.

15. GSE and Facility Concept Definition

After the systems review of the airborne equipment, the GSE and facility concepts are fully defined (C-15) so that selection can be made.

16. GSE and Facility Concept Evaluation & Selection

Once the alternative concepts have been fully defined, they are evaluated by central systems engineering and the best concepts selected (B-16). The activities of D-16 are involved in the evaluation and selection process. This activity results in GSE and facility system element concept selection (E-16), and the results are integrated in the requirements and definition baseline.

17. GSE & Facility Performance Design Analysis

A performance design analysis is conducted by GSE and facility technical disciplines (C-17) concurrently with an integration activity performed by the central systems disciplines (B-17). The basis for these activities is the requirements contained in the requirements and definition baseline (A-17). The output of the performance design analysis is input into the baseline (A-17) and the expanded concept models (E-17). The activities of D-17 are performed in the process.

18. GSE & Facility Performance Sizing

Performance sizing of GSE and facility equipment is performed by GSE and facility technical disciplines using the activities of D-18. The information source for the activity is that contained in the central systems requirements and definition baseline (A-18). The output of the performance sizing operation is integration in the baseline (A-18). Concurrently with the performance sizing operation, an integration activity is performed by central systems to assure compatibility of the results of the performance sizing activity with the total system (B-18). The output of the performance sizing and integration activities results in the sizing of GSE and facility systems elements.

19. GSE and Facilities Design Definition

Subsequent to the performance sizing of GSE and facilities, definition of the design of these elements occurs (C-19) resulting in system element definition (E-19) which is integrated in the requirements and definition baseline (A-19).

20. A/B Equipment Design Definition Update

After the GSE and facility design has been defined, the airborne equipment technical disciplines perform a definition update of the airborne equipment (C-20) resulting in an update of the previously defined airborne equipment (E-20). The results of this activity are integrated in the requirements and definition baseline (A-20).

21. Operations Update

After the airborne equipment definition update and the GSE and facility definition, an update of the total system operation is performed (B-21) assuring that the system elements, as defined, are compatible with the total system. Information for this update comes from the requirements and definition baseline (A-21) and the system elements (E-21). The output of the operations update activity is integrated in the requirements and definition baseline (A-21).

22. Requirements and Definition Review

A requirements and definition review is held by central systems engineering to assure that the systems elements, as defined, and the operations concepts as updated, will meet the total system performance and definition requirements (B-22). All activities that have occurred prior to this point in time and the requirements contained in the central system integrated requirements and definition baseline form the basis for this review. Approval of all activities prior to this point in the development process results in approved airborne and ground system element definition (E-22) and sets the stage for the design phase that follows.

## APPENDIX

1. SCOPE

This document defines mission and system criteria necessary for the definition of individual subsystem elements. This criteria is a directive to all products (subsystems) and functional (vehicle performance, reliability, safety, logistics, etc) disciplines for specification and hardware development.

2. APPLICABLE DOCUMENTS

3. REQUIREMENTS

3.1 Program Definition

3.1.1 General Description

3.1.1.1 Airborne Items

3.1.1.2 Operation Ground Support Equipment

3.1.1.3 Facilities

3.1.1.4 GFE

3.1.2 Missions

3.1.2.1 Launch Rates

3.1.2.2 Launch Risks

3.1.2.3 Hold Requirements

3.1.2.4 Launch Date

3.1.2.5 Launch on Time

3.1.2.6 Launch Window

3.1.2.7 Reaction Time

3.1.2.8 Payload Description - Crew, Type, Size, and Weight; Instrumentation Type, Size, and Weight

3.1.3 Operational Concepts

3.1.3.2 Flight Duration

3.1.3.3 Maneuvers

3.1.3.4 Recovery (Data or System)

3.1.3.5 Mission States

3.1.3.6 Baseline Reference Flight Path Trajectory

3.1.4 Organizational and Management Relationships

3.1.5 Systems Engineering Requirements

3.1.6 GFP

3.1.7 Critical Components

3.2 Characteristics

3.2.1 Performance

3.2.2 Physical

3.2.3 Reliability

3.2.3.1 System Reliability (Failure Modes, Redundancy, Useful Life)

3.2.3.2 Reliability, Apportionment to System Elements

3.2.4 Maintainability

3.2.4.1 Maintainability

3.2.4.2 Maintainability Downtime Allocations to System Elements

3.2.5 Operational Availability

3.2.6 Safety

3.2.6.1 System Safety

3.2.7 Environment

3.2.8 Transportability/Transportation

3.2.9 Storage

3.3 Design and Construction Standards

3.3.1 Selection of Specifications and Standards

3.3.2 General

3.3.2.1 Electromagnetic Interference Requirements

3.3.2.2 Man/Machine Requirements

3.3.3 Design Standards

3.3.4 Moisture and Fungus Resistance

3.3.5 Corrosion of Metal Parts

3.3.6 Contamination Control

3.3.7 Coordinate Systems

3.3.8 Interchangeability and Replaceability

3.3.9 Identification and Marking

3.3.10 Workmanship

3.3.11 Human Performance/Human Engineering

3.3.12 Computer Programming

3.4 Logistics

3.4.1 Maintenance

3.4.2 Supply

3.4.3 Facilities and Facility Equipment

3.5 Personnel and Training

3.6 Interface Requirements

3.6.1 Intraprogram Interface Requirements

3.6.1.1 Vehicle/Ground Interface Concept Criteria
Criteria must be defined to allow design definition of ground systems that will operate and mate compatibly.

3.6.1.1.1 Umbilicals

3.6.1.1.1.1 Location Constraints

3.6.1.1.1.2 Separation Requirements

3.6.1.1.1.3 Type—manned, Fly-away, Remote

3.6.1.1.2 Checkout Criteria

3.6.1.1.2.1 Subsystem Checkout Requirements

3.6.1.1.2.2 Integrated System Checkout Requirements

3.6.1.1.2.3 Malfunction Detection Requirements

3.6.1.1.2.4 Countdown Requirements

3.6.1.1.2.5 Inflight Checkout Requirements

3.6.1.1.3 Hold Criteria

3.6.1.1.4 Shutdown (kill) Criteria

3.6.1.1.5 Signal Interfaces

3.6.1.1.6 Facility Requirements

3.6.2 Intraproject Interface Requirements

3.7 Requirements for Program Elements

3.7.1 Facilities

3.7.1.1 Location of Operational Installation

3.7.1.2 Location of Special Test Installations

3.7.1.3 Ambient Environments at Installations

3.7.1.4 Test Range and Support Systems Ground Rules and Assumptions

3.7.2 Vehicle Design Criteria
Criteria for the following items must be developed for an airborne flight vehicle or payload.

3.7.2.1 System Concept Description

The fundamental concept of each system element selected during concept feasibility phase is defined and described. For example, concept studies may establish a basic vehicle type and configuration--number of stages, use of an existing engine, booster, or facility, etc.

3.7.2.2 Reliability Requirements

3.7.2.2.1 Design Goals and Mission Success Requirements

3.7.2.2.2 Launch on Time Requirements

3.7.2.2.3 Allocations to System Elements

3.7.2.3 Performance Requirements

3.7.2.3.1 Payload Capability

3.7.2.3.2 Mission Capability

3.7.2.3.3 Maneuvering Requirements

3.7.2.3.4 Accuracy Requirements

3.7.2.3.5 Expected Life

3.7.2.3.6 Reaction Time

3.7.2.3.7 Propulsion Systems

3.7.2.3.8 Guidance Systems

3.7.2.3.9 Flight Safety Systems

3.7.2.3.10 Manfunction Detection Systems

3.7.2.3.11 Life Support Systems

3.7.2.3.12 Structures

3.7.2.3.13 Electrical Power Systems

3.7.2.3.14 Attitude and Velocity Correction Systems

3.7.2.3.15 Hydraulic Systems

3.7.2.3.16 Gas Systems

3.7.2.3.17 Fluid Systems

3.7.2.3.18 Ordnance Systems

3.7.2.4 Performance Allocations

3.7.2.4.1 System Element Allocations

3.7.2.4.2 Weight Allocations

3.7.2.4.3 Error Allocations

3.7.2.4.4 Risk Allocations

3.7.2.5 Interface Criteria System, Element to System Element

3.7.2.5.1 Performance

3.7.2.5.2 Functional

3.7.2.5.3 Physical (mechanical and electrical)

3.7.2.5.4 Signal

3.7.2.5.5 Man/Machine

3.7.2.6 Loads Criteria

3.7.2.6.1 Launch Loads

3.7.2.6.2 Prelaunch Loads

3.7.2.6.3 Transportation Loads

3.7.2.6.4 Inflight Loads

3.7.2.6.4.1 Aerodynamic

3.7.2.6.4.2 Maneuvering

3.7.2.6.4.3 Acceleration

3.7.2.6.4.4 Staging

3.7.3.1.7 Subsystem Checkout Systems

3.7.3.2 Performance Requirements for Support Systems

3.7.3.2.1 Propellant Servicing Units

3.7.3.2.2 Water Systems

3.7.3.2.3 Gas Systems

3.7.3.2.4 Hydraulic Systems

3.7.3.2.5 Environmental Control Systems

3.7.3.2.6 Electrical Systems

3.7.3.2.7 Air Conditioning Systems

3.7.3.2.8 Communications Systems

3.7.3.2.9 Tracking Systems

3.7.3.2.10 Handling Equipment

3.7.3.3 Performance Requirements for Facilities

3.7.3.3.1 Fabrication Facilities

3.7.3.3.2 Acceptance Facilities

3.7.3.3.3 Test Facilities

3.7.3.3.4 Support Facilities

3.7.3.3.5 Training Facilities

3.7.3.3.6 Launch Facilities

3.7.3.3.7 Recovery Facilities

3.7.3.4 Reliability Requirements

3.7.3.4.1 Design Goals and Mission Success Requirements

3.7.3.4.2 Launch on Time Requirements

| | |
|---|---|
| 3.7.3.4.3 | Allocations to System Elements |
| 3.7.3.5 | Maintainability Requirements |
| 3.7.3.5.1 | Design Goals |
| 3.7.3.5.2 | Downtime Allocations |
| 3.7.3.6 | Interface Criteria - System Element to System Element |
| 3.7.3.6.1 | Performance |
| 3.7.3.6.2 | Functional |
| 3.7.3.6.3 | Physical (mechanical and electrical) |
| 3.7.3.6.4 | Signal |
| 3.7.3.6.5 | Man/Machine |
| 3.7.3.7 | Safety Requirements |
| 3.7.3.8 | Environmental Requirements |